

Demonstration of Boost Phase Control Algorithm

John P, Kajs, SAIC, Austin TX

Dr. Peter Mongeau, ePower, Westborough MA

Dr. Terry Burke, Ghassan (Gus) Khalil, Byron Wong, TARDEC, Warren MI

Under the TARDEC Power & Energy program a different control algorithm is being tested for hard switched permanent magnet machine power conversion. This control algorithm can be substituted for conventional boost PWM converter to reduce losses in both the inverter and the generator where applicable. Boost phase control (BPC) reduces the switching frequency of the hard switched inverter to the fundamental frequency of the machine. It is different than six-step converter control in that it purposely includes as an integral part of the control algorithm a non-gated part of the cycle. This algorithm can be used for both motoring and generating operation and is most applicable where the modulation ratio of the inverter is near 100%, though depending on the machine and converter characteristics can have benefit at lower modulation ratios. This algorithm has been tested initially on a low power testbed (to debug hardware implementation) and has now been tested with a COTS liquid cooled inverter and a high power COTS PM machine. A basic description of the BPC algorithm and the experimental setup plus test results will be presented with a comparison of the results of using the same hardware (inverter and machine etc) with PWM at various switching frequencies and boost phase control. Data will include both model and experimental waveforms and harmonic content results along with loss measurements both electrically and thermally for both the machine and the inverter. Areas of operation where BPC shows improvement over PWM will be described.

Basic Approach

For permanent magnet machines, at the upper end of the speed range, conventional inverters begin to run out of available voltage to drive the winding currents for obtaining the desired performance. Near this region, there can be advantages to dramatically reducing the switching frequency and going to switching algorithms similar to six step regulation where the power flow is controlled by adjusting the phase shift between the applied voltage at the terminals of the machine relative to the back-emf of the machine. One of the downsides of six step algorithms is that you are reduced from 2 degrees of freedom for the voltage with PWM (amplitude of the voltage and phase shift between the terminal voltage and back-emf) whereas with six-step, you are reduced to just the phase shift. Utilizing BPC with a Y configured electric machine is similar to six-step except that the gating purposely introduces periods where a phase is not actively gated either high or low. This results in a low switching frequency control methodology which has some level of control for both the amplitude and the phase of the terminal voltage. Basically, the gating can be defined by a delay angle from when the back-emf becomes the highest voltage (both positive & negative sides) plus an on duration for the gate. The basic approach for use of BPC is that it is expected that at the lower speed ranges, the user will be better off using something like standard PWM and as the speed gets higher the user will begin utilizing BPC at the higher speed range.

The basic test setup was created using a combination of COTS and existing hardware. The inverters utilized are liquid cooled inverters with the available vendor provided TI '2812 motor control board for doing the gating control. The machine is a standard axial gap PM machine with each set of windings connected in a Y connection to their own inverter. There are also some external chokes installed between the machine windings and the inverters. These choke inductors add approximately 50 uH to the 60 uH of the winding inductance of the generator to allow this standard PM machine to be flux weakened and operate adequately from a 600 Vdc bus up to 3300 RPM (without the additional inductance the reactive current for flux weakening at the high speed would be excessive). The coolant flows, inlet and outlet temperatures for both the inverters and machine were instrumented to estimate the heat removed during the tests. Electrical measurements were made with power analyzers having 100,000 samples per channel and 8 channels per analyzer set to sample at 5 MS/sec. The analyzers have 4 current inputs that were connected with closed loop hall effect current sensors rated for >100 kHz response rate and 4 voltage inputs were directly connected to the analyzers without signal conditioners outside of the internal power analyzer inputs. Voltage measurements were made from all of the points labeled A, B & C to a floating neutral and from P to M for the DC along with the 4 shown currents (I_a , I_b , I_c & I_{dc}) for the main measurements. In addition, measurements were made across the inductor windings with these same I_a , I_b & I_c currents as well to characterize the impact of the inductors (both impedance and loss estimates).

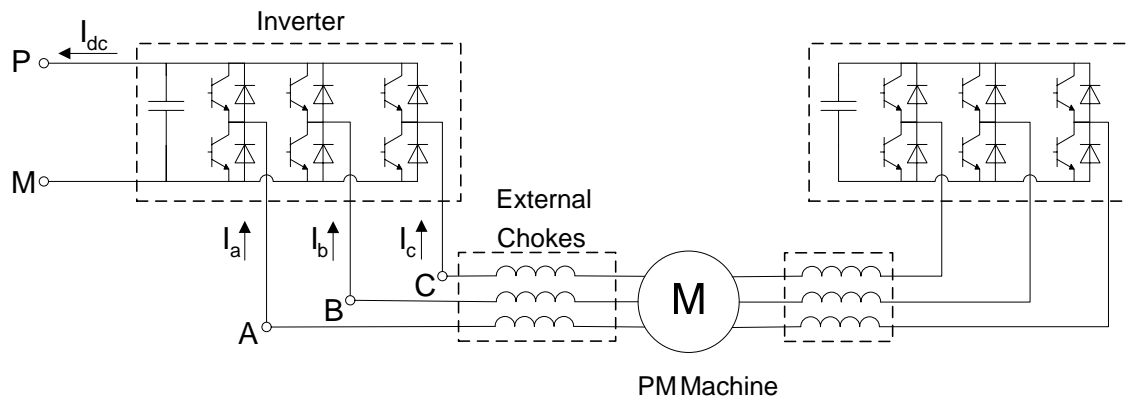


Figure 1. Basic Experimental Setup.

During these tests, only one set of windings and one of the inverters were actually used. In order to go to the full generator and engine ratings without worrying about thermal margins, it is necessary to use both sets of windings and both inverters. In order to simplify things for these initial tests the right half of the above system was unused. While not using this second half but still having it connected to the bus (in case of a failure this 2nd inverter would act as a diode rectifier to stop engine runaway), this does limit the operation from a 600 volt bus to below ~2500 RPM. To begin investigating the regions where flux weakening is required will necessitate either completely disconnecting this 2nd inverter or else using both inverters simultaneously. In addition to the above main power system hardware, a simple interface between the resolver coming from the generator to emulate hall effect signals for the DSP digital interface was created from a COTS resolver to encoder evaluation board and a simple FPGA board to give the inverter angular information about the generator for it's control.

Table 1. Nominal Component Parameters

Machine rated speed	2860 RPM
Machine continuous power at 2860 RPM	336 kW
Machine continuous current	370 Arms
Machine pole pairs	14
Machine winding resistance (per winding)	22 m Ohms
Machine winding inductance (per winding)	60 μ H @ 500 Hz
Machine nominal coolant rated temperature	49 C
Machine nominal coolant rated flow	7 gpm (3.5 gpm per stator)
Machine # stators	2
Machine Windings per stator	3
Machine Fund Vconst (per winding)	0.23 Vrms, L-L per RPM
Inverter nominal continuous coolant rating	300 Arms (at 5 kHz switching frequency)
Inverter device voltage rating	1200 Volts
Inverter capacitor max allowable voltage	900 Volts
Inverter max switching frequency	15 kHz
Inverter nominal coolant rated temperature	50 C
Inverter nominal coolant rated flow	2-3 GPM
Choke Inductance	50 μ H @ 60 Hz
Choke Fund Amps	500 Arms @60 Hz

Testing Performed

During the testing, 3 sets of tests were performed, 1 set with the boost phase control, plus 2 using PWM and field oriented control (FOC) at both 5 kHz and 10 kHz PWM frequency. The same basic FOC calculation routine for estimation of the real (Iq) and reactive (Id) currents was used for all 3 systems (as much commonality for the control code as possible was used for all 3 cases). A test matrix of desired operating points (speeds and Iq) was created. Speeds and power values which would require flux weakening were avoided for this initial round of testing. For the PWM cases, standard FOC techniques updated at the switching frequency adjusting the Vd & Vq based on the observed Id & Iq and desired Id and Iq (for these cases Id desired was always zero since there is no

flux weakening). For the BPC, at a given speed the observed I_q was compared to the commanded I_q and the gating on time was adjusted to get to the commanded I_q plus the delay angle was adjusted based on the observed reactive (I_d current) to minimize it. The original coding for the delay angle in the BPC only allows this angle to be positive values which results in the fundamental of the current always having a significant reactive (I_d value). This limitation for the delay angle results in the BPC having higher fundamental current for the same I_q (torque/mechanical power) points from the system and thus higher losses due to the fundamental frequency components for both the inverter and the machine. This present control hardware limitation is not representative of the ability of BPC and thus valid conclusions of the effectiveness of BPC can not be reached based on the available test data that has presently been collected. The full test matrix (most of these points were reached during testing) is shown below

Table 2. Full System Test Matrix.

Speed (RPM)	I_q Commands (Amps Peak)	Notes
1000	50, 100, 150 & 200	Waited for approx thermal equil. for 200
1250	50, 100, 150 & 200	
1500	50, 100, 150 & 200	Waited for approx thermal equil. for 200
1750	50, 100, 150 & 200	
2000	50, 100, 200 & 300	Waited for approx thermal equil. for 300
2250	50, 100, 200 & 300	
2500	50, 100, 200 & 300	Flux weakening required for higher I_q

The speeds where the most complete data was collected for all 3 sets of data are the 1000, 1500 & 2000 RPM cases and they will be primarily discussed throughout this report.

Inductor Characterization

The inductors inserted between the inverter and generator are designed primarily for 60 Hz operation to reduce the impact of inverter harmonics on machines. However, the manufacturer advertises that they can be used at higher frequencies at reduced current levels, but there is limited manufacturers data (such as losses and inductance) at these higher frequencies. A compilation of power analyzer data measuring just the inductor voltage and currents was performed to estimate the equivalent resistance and inductance at the fundamental frequencies tested for each dataset run.

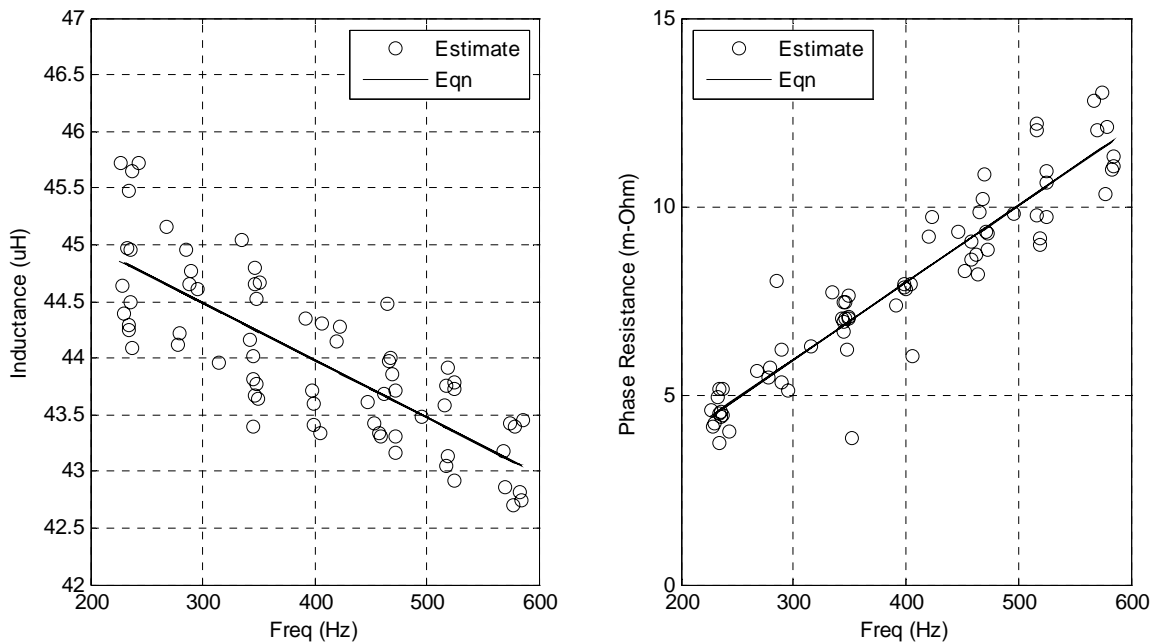


Figure 2. Compilation of Inductor Measurements.

This inductor analysis was done by calculating just a fundamental current and fundamental voltage (complex in both cases) and then doing a simple $Z=V/I=R+j\omega L$ and plotting vs the fundamental frequency. From this data, it

appears that a simple linear curve fit for the inductance vs frequency for up to 600 Hz will give the inductance of the inductor within ~5% ignoring any saturation or current amplitude effects with the inductance and in addition this curve fit would estimate the inductance at 60 Hz of ~46 μH which is ~90% of the datasheet stated inductance value of 50 μH . In addition, a linear curve fit for the resistance of the inductance vs frequency also appears to reasonably fit the data (a linear curve fit wasn't necessarily expected to be a reasonable choice for that data).

Inverter Characterization

For the inverter losses the primary method used to estimate the losses was based on the heat removed by the liquid coolant. In the case of the inverters, they are mounted on stands with the base of the stands mounted to the floor of the HERMIT chassis. As a result of the mounting scheme, it is believed that the majority of the heat goes in from the inverter losses and the heat is removed through the liquid coolant. Because of the relatively short thermal time constant of the inverter (reached reasonable thermal equilibrium after about a minute at an operating point) and the relative thermal isolation of the inverter (this could be improved by adding insulation for higher accuracy) this is considered to give reasonable values. The exact values of losses are not claimed to be highly accurate (probably no closer than 20%), however since the exact same setup was used for all 3 sets of data (all data was collected within a couple of days after set up), it is believed the relative accuracy between tests should be quite good. Below is shown an example of the data used to estimate the inverter losses for one set of the data. The 'Inv Heat' is calculated based on the simple equation $P = C_p F_{\text{mass}} (T_{\text{out}} - T_{\text{in}})$ using measured flow rates from flow sensors, typical fluid properties and measured inlet and outlet temperatures from thermocouples. The vertical lines in the charts below show when in time the time domain waveforms were sampled on the power analyzers (shown as markers in the lower plot) to estimate the electrical power flow and operating conditions. The heat removed was estimated for each of the operating points by taking a 60 second average of the heat removed at the time of the electrical sample.

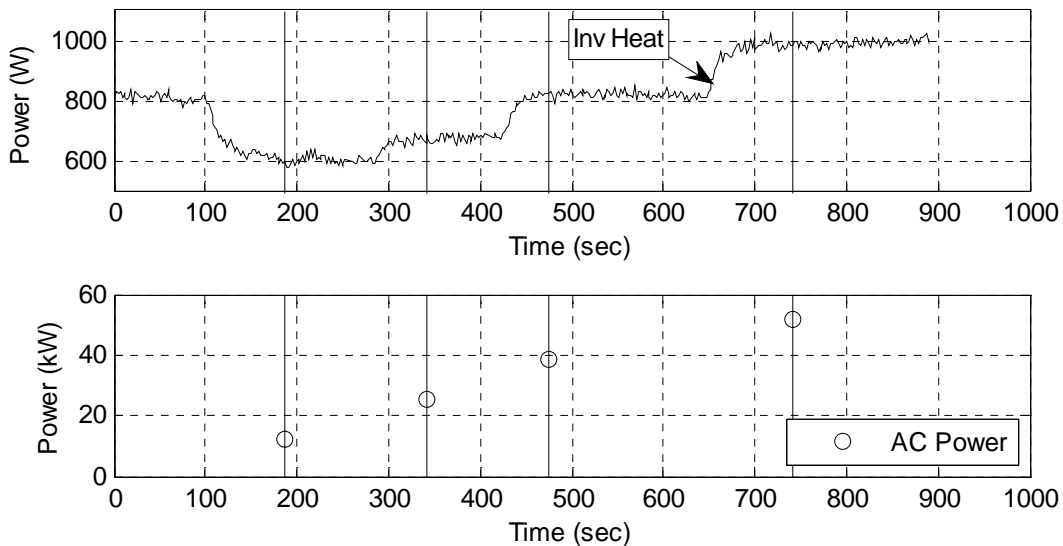


Figure 3. Inverter Losses for 5 kHz PWM at 1500 RPM.

In addition to the thermal estimate of heat removed, the actual operating conditions for the inverters were estimated from the power analyzer data. This was done by calculating the fundamental (complex quantities including amplitude and phase) for both the voltage and currents from the data (including an estimate of the fundamental frequency). Below are a couple examples typical of the data collected and the extraction of the fundamental values from the measured data. Something of particular note is the fact that for the PWM case, the current is leading the voltage while for the BPC case the voltage is leading the current. In addition, it can be noted that the fundamental current has a higher amplitude for BPC than the PWM case. As noted earlier, this is an artifact of the angular limitation present in the hardware at this moment in time and is not representative of BPC in general and is being rectified to enable a valid comparison to be completed between PWM and BPC.

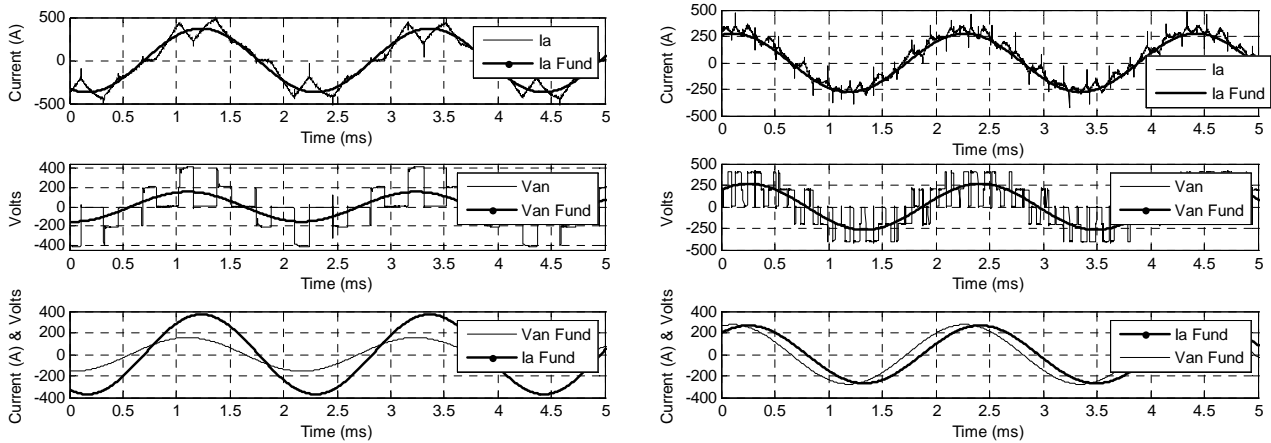


Figure 4. Power Analyzer Data at 2000 RPM & max current for BPC (left) and 10 kHz PWM (right).

Once these inverter operating conditions were determined experimentally for the PWM cases, the operating conditions (DC voltage, AC voltage fundamental, AC current fundamental, power factor between current and voltage, fundamental and switching frequency) were then plugged into the online tool from inverter vendor to calculate the estimated losses based on the inverter components. There is no apparent estimate of the impact of harmonic distortion on the vendor inverter losses for the online tool. Below is plotted the results of the losses removed thermally along with the vendor calculation of the estimated inverter losses for the PWM cases as a function of operating conditions.

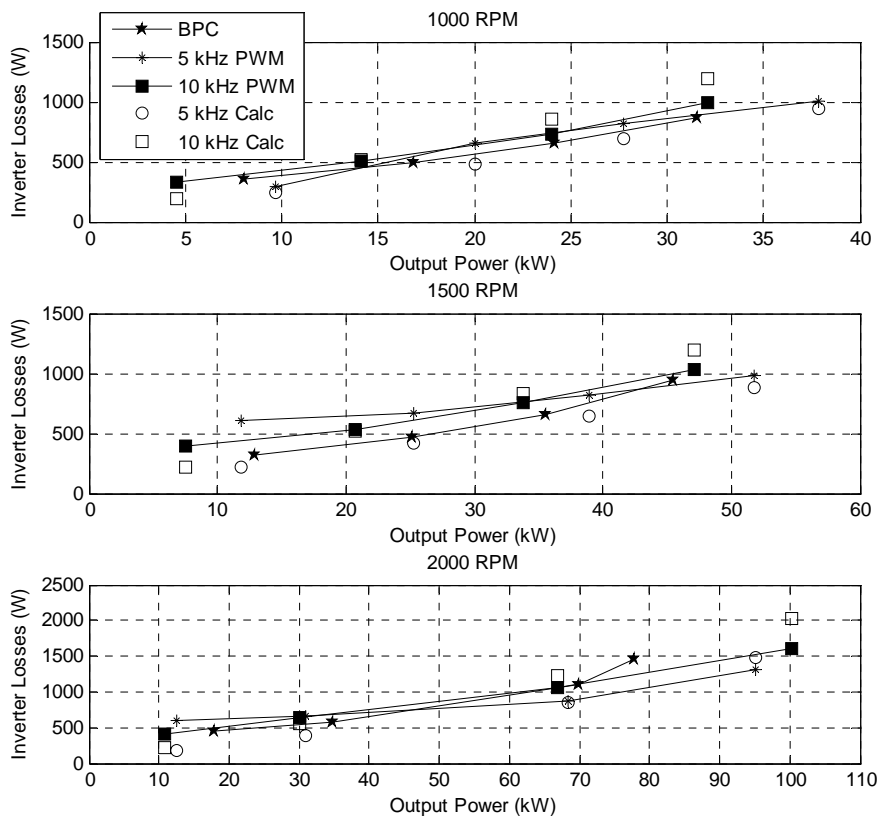


Figure 5. Estimated inverter losses for selected cases.

For the inverter losses there is reasonable agreement between those estimated by the vendor and those estimated from the thermal measurements. The thing which jumps out is that there is little separation in losses
UNCLAS: Dist A. Approved for public release

between the 3 cases measured. Looking at the data, it appears that the primary reason for this is that the BPC was operating at the higher fundamental current than is necessary due to the angle limitation presently in the hardware which creates un-necessary additional losses for the BPC cases shown here.

Machine Characterization

The plan was to estimate the losses in the machine from both electrical measurements (to be described shortly) and also from the thermal heat removed from the cooling of the machine. After making the measurements, and analyzing the data, it was determined that the present set of generator cooling data is not useful for the intended purpose. The biggest issue is that whereas the inverters are relatively thermally isolated from the rest of the components, the generator is directly mounted to the largest heat source of the entire vehicle (the engine). After looking at the data with electrical loading, another set of thermal data without any electrical loading on the generator at all (open circuit) was collected. The results indicated that the experimental setup will need to be instrumented a little more carefully and the runs extended significantly to minimize the disturbance to the heat removed from the generator through the generator coolant. At the present time, estimates of the machine losses based on analysis of the power analyzer data can be made which can give some understanding of the relative losses between the presently collected BPC data and the PWM data. For illustration purposes, the same datasets shown earlier (highest power for BPC and 10 kHz PWM at 2000 RPM) will be used. Afterward, a compilation of all the test cases will be shown.

A large amount of this analysis is done in the frequency domain which is useful based on the fact that the back-emf of the machine really only has 2 significant components when connected into a Y connected configuration the 1st and 5th harmonics. As a result of the back-emf harmonics being concentrated, very little electromechanical power is transferred from the engine shaft at the higher frequencies above the 5th harmonic of the fundamental. There is some that occurs based on action like an induction motor, but based on the relatively large slip relationships these will tend to be quite small and most of the power at the higher frequencies should be into the machine and will mostly become additional losses within the machine. Unfortunately, though this approach works quite well for PWM operation where there is minimal 5th harmonic applied to the terminal voltage, this is approach is problematic for the BPC case. As a result of the non-trivial 5th harmonic of voltage for the machine and the fact that the BPC algorithm in effect also has a 5th harmonic for the voltage, it is feasible for the BPC to have net power going into the machine at the 5th harmonic but rather than having this power go into losses, this power could be providing motoring action to the shaft and not be an actual electrical loss. It will be necessary to obtain good thermal measurements to know for sure.

For the frequency domain analysis, the 1st thing which is done is to calculate the frequency domain components of the currents and voltages through a standard DFT (Discrete Fourier Transform) although in tools like Matlab the operation is actually mis-labeled as performing an FFT. It is then possible to scale the complex voltages and currents in the frequency domain so that the amplitudes in the frequency domain have numerical relevance to the original quantities in the time domain. After scaling the voltages and currents it is then possible to calculate the real power at each frequency with $P = \text{real}(V * \text{conj}(I))$. After calculating the power as a function of frequency, it is possible to sum up the power over a range of frequencies to provide better understanding of what is occurring.

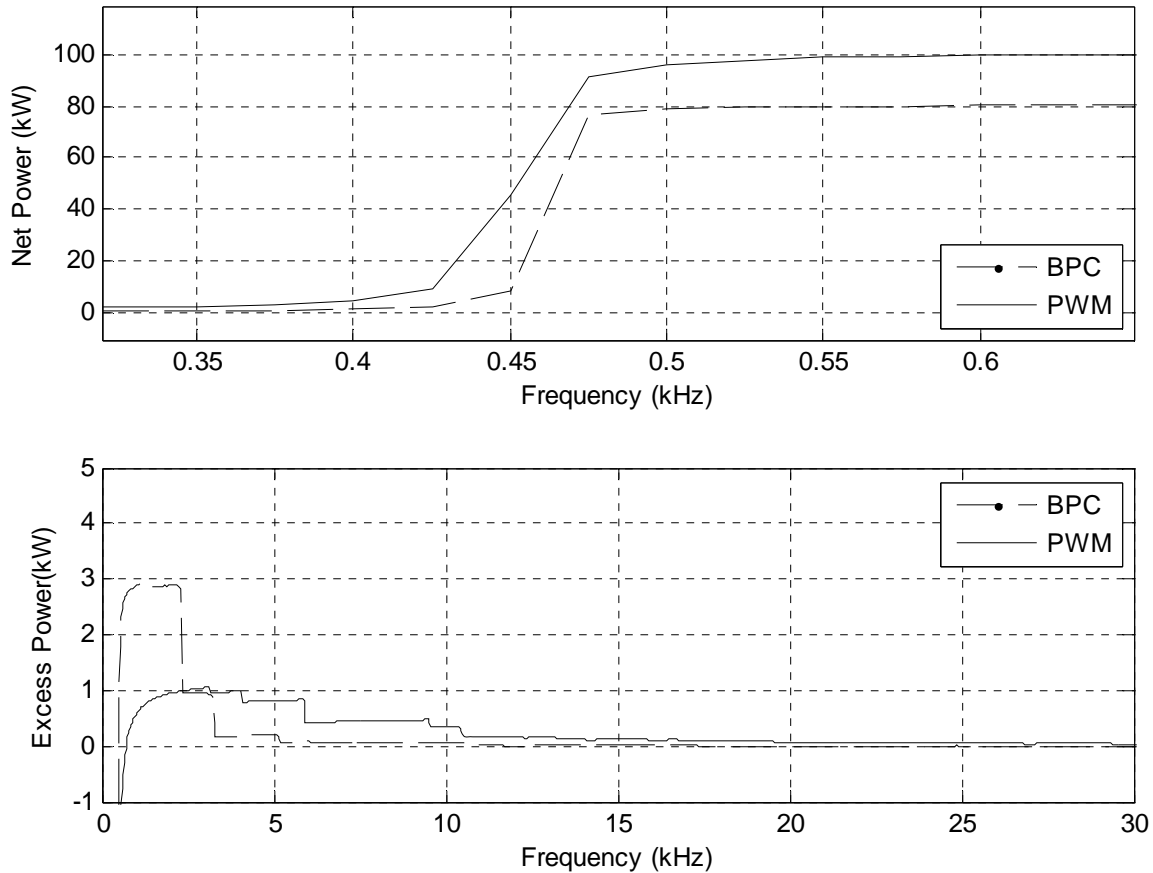


Figure 6. Frequency Domain Power for Tests.

In the plots shown above, the top is the cumulative sum of the power and it is easy to see that the power increases suddenly for both cases right at the frequency for the fundamental around 460 Hz. The lower plot is the same data except that the frequency scale is expanded and the power scale is offset by the total power calculated for each case. For the BPC case, it is easy to see the power being returned to the machine at 5x the fundamental frequency of ~2300 Hz while for the PWM case, the power is returned to the machine (the trace goes down when power is returned to the machine) at multiples of the switching frequency plus & minus multiples of the fundamental frequency as expected. Additional analysis will need to be performed taking into account the higher order harmonics along with their phase shift (particularly the 5th) before good solid information will be able to be gleaned from this data about machine losses.

Showing a composite of the selected 12 datasets, gives some indication of the loss comparison. However, there are 2 things which are still to be resolved for the estimate of the BPC losses. The 1st is that the angle limitation for the BPC in the test hardware needs to get fixed which will lower the fundamental current for the BPC so that the fundamental current is similar to the PWM cases which will lower the BPC fundamental losses. The second is determining whether the power returning to the machine for the 5th (& 7th) harmonic with BPC are all losses or whether some of that is actually returned as mechanical motoring torque (probably) rather than losses.

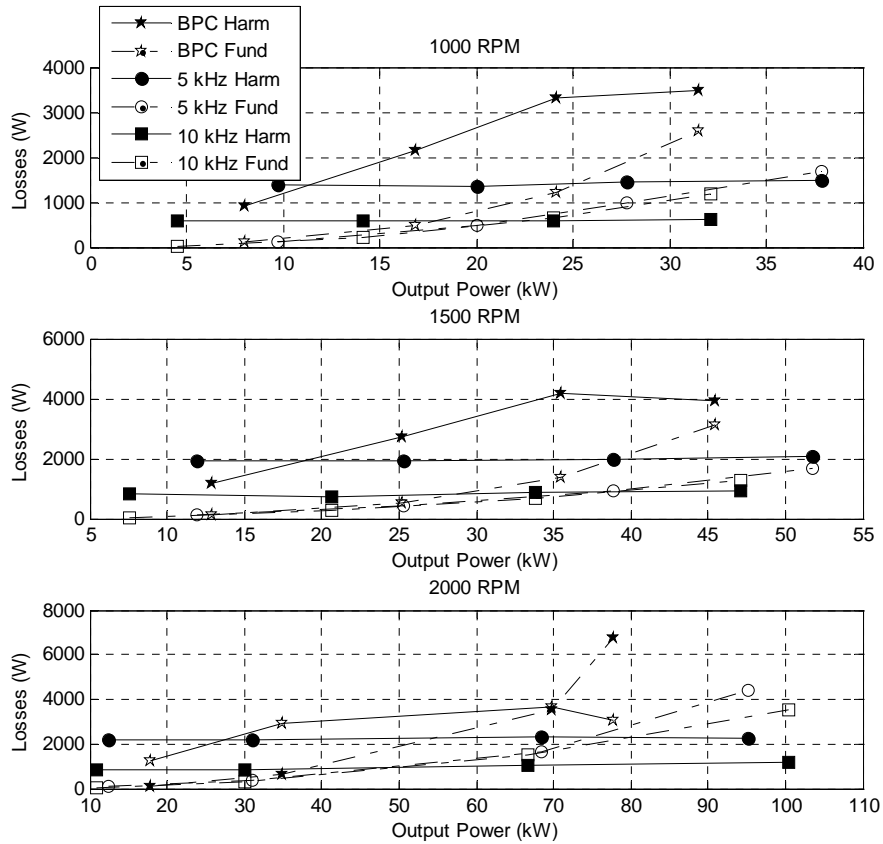


Figure 7. Machine Power Calculations for Selected Datasets.

Path Forward

Modifications are in process for the BPC gating algorithms so that the angle can be advanced to reduce the fundamental frequency currents for the same output power. In addition, the thermal instrumentation on the generator will be improved to allow the machine loss removal to be better estimated. The final upgrade will be related to the analysis to incorporate some of the higher frequency harmonics into the analysis of the response. Finally, after all of that is implemented the testing will be completed and will also cover the full operational range of the generator including significant flux weakening where BPC should be significantly more advantageous than the operating points initially tried.