Oscilloscope Traces in Pulsed Circuits

Part 2. Rotating salient pole motors

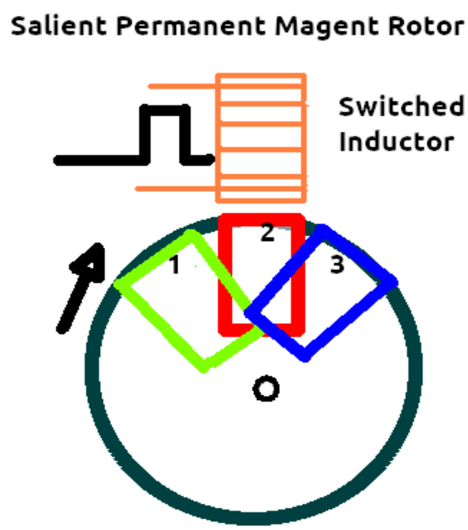
The situation covered in Part 1 will now be extended for the case of pulsed inductors as used in the context of a salient pole permanent magnet motor. There are many examples of the pulsed battery charging technique being used in conjunction with torque production, in a quest for shaft power and simultaneous battery recharging. Such is the basis for the Bedini SG and its variations. They all are similar in that the the rotor of the motor has some number of permanent magnets which are either pulled or pushed into rotation by the pulsed inductors. The idea has been put forward that if one is pulsing an inductor in order to create an abrupt battery charging pulse, one might as well use the associated magnetic field to generate torque in a rotor, as that torque can be had “for free”. While there is demonstrated merit to the technique, it is not at all straightforward to say “for free”, as there are Lenz law and other interactions that must be taken into consideration, as will be seen.

The main factors which need to be specified in making one of these salient pole machines are:

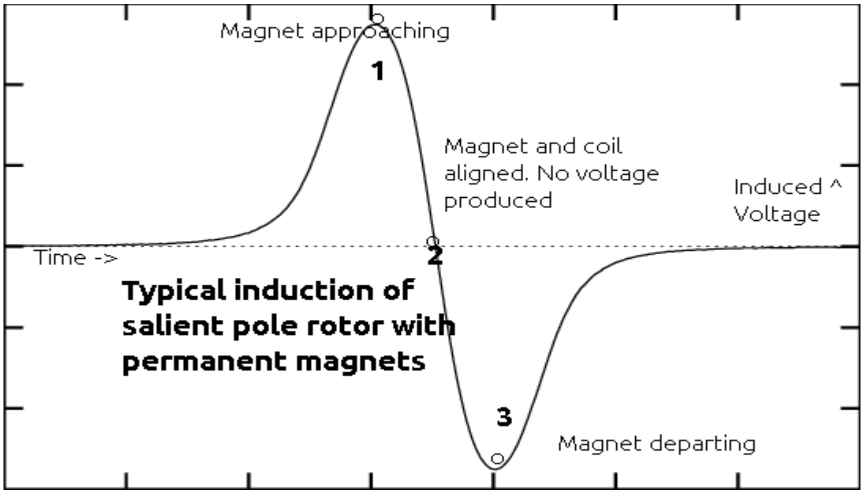
1. Intended RPM of the rotor
2. Number of poles on the rotor (assuming all outward facing poles are the same, N or S)
3. Diameter of the rotor, which is determined by pole spacing
4. Inductance of the pulsed motor drive coil(s)
5. Voltage used to energize coils

These factors are all interrelated, and I will not be able here to do more than give broad indications. The main effort is towards narrowing the design choices for what sort of inductance is best for the drive coils. This is a topic that I have not seen covered, and most people appear to be using cut and try methods, which can be labor intensive.

To begin, here is a simplified diagram of the usual salient pole rotor passing by a pulsed coil:



The magnet is approaching the coil at 1, is aligned with the coil at 2, and is passing away from the coil at 3. If the rotor were to be turned by some external torque (for example, a hand drill) and an oscilloscope is placed across the terminals of the inductor, the resulting voltage induced in the coil would look like the graph below. The voltage is dependent on the magnetic flux, the inductance of the coil, and the rate of speed at which the magnet passes. The symbol for Phi is used to indicate the flux, and Faraday’s law of induction says that V= -dPhi/dt, or voltage is directly proportional to the minus rate of change of the flux through the coil windings.



The main point here is that the peaks of voltage above correspond to the angular positions of the rotor which produce the most flux change, and which also happen to be the same (or very close) positions which are most effective for torque production when the drive coils are energized. At positions beyond 1 or 3, away from the coil, assuming sufficient spacing of the magnets, the efficiency of generating torque is reduced due to excessive distance, since there is a 1/r^2 dependency on magnetic force. At position 2, no torque is generated due to the alignment of the magnet and the coil. Of note, the classic SG circuit in attraction mode, with its self excited switching, draws its maximum drive current right at that alignment point, just as the field is about to flip and the drive shuts off. That is not the most efficient arrangement for torque generation, as one would prefer that maximum point to be closer to position 1. Those who go to some form of variable electronic switching (e.g. optical sensing) end up switching in the vicinity of position 1 in attraction mode, or position 3 in repulsion mode. In order to narrow the options for the best timing, it is necessary to know the length of time each pole interacts with the drive pulse.

The calculation for the number of pulses per second the rotor gives is: (RPM/60) * N, where N is the number of poles. For example, a rotor with 8 poles turning at 1800 RPM will produce 240 pulses per second. That is the number of torque producing interactions per second, as well as the number of battery charging pulses per second. What rate is optimum is an open question at this point, but some hundreds of pulses per second would look to be at least a practical value for most experimenters. The reciprocal of 240 pps is 4.2 msec per pulse, which means that the length of each drive pulse needs to be significantly shorter than this value to avoid interacting with a distant magnet rotating into position.

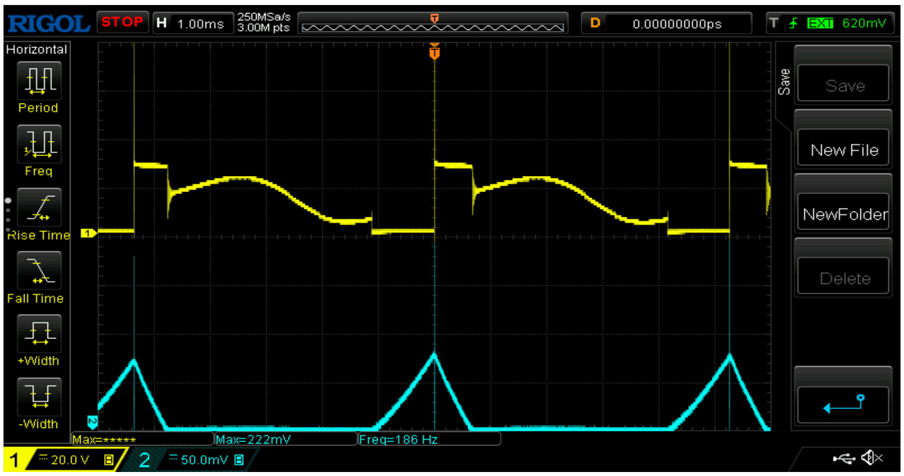
The strength of the magnetic force and hence torque which each pulse produces will be proportional to the number of Ampere-turns in the excited coil times the magnet field strength. This is the usual nIB (turns*current*B field) term that is common in all motor equations. A large number of turns would appear to be attractive due to the larger force generated, as demonstrated by Joseph Newman’s designs, but this comes with the disadvantage of high coil resistance (to say nothing of extravagant quantities of copper) , and the large inductance brings with it a decrease of di/dt = V/L, and hence a slowing of the pole interaction. Both factors necessitate a high operating voltage in order to produce practical torque and RPM.

If higher RPM is desired for a given voltage supply, then the inductance of the motor coil must be reduced in order to produce sufficient Ampere-turns in a short amount of time, but this is traded off against the reduced peak magnetic force. Again, higher voltage can compensate for this reduction, but that brings in more stringent requirements in the switching components, which need to be fast and tolerate high voltage and current.

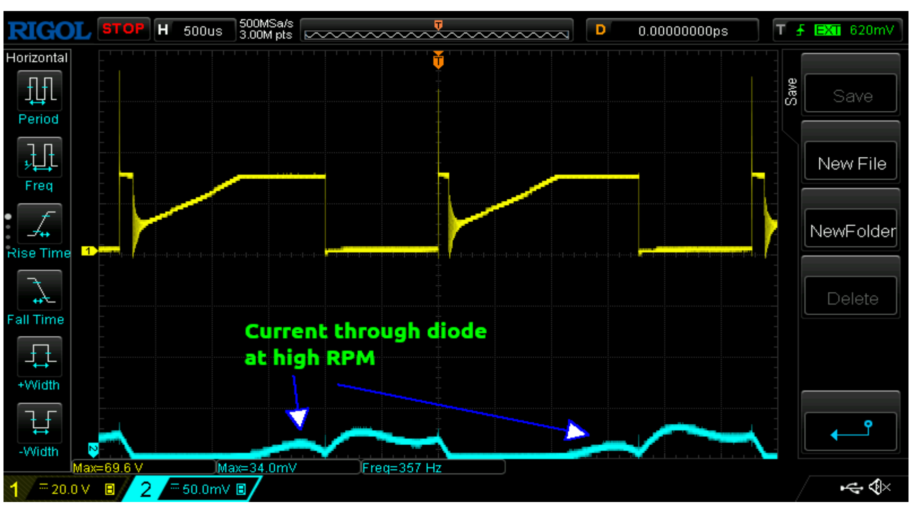
Returning to the rule of thumb given in Part 1, 1 volt across 1 milliHenry will cause 1 amp of current increase per millisecond. Assuming some arbitrary value of current draw in the ~10 amp peak range, with about 1mSec pulse width on time (assuming classic SG mode of operation), with a 12 volt supply, something on the order of 1.2mH is indicated for the total inductance. The use of the same number of coils as poles is a good technique, so this value is the total amount of inductance, whether formed by parallel or series connection. Where the optimum arrangement lies is still a question, but the foregoing can at least give some direction. It is possible to use various series/parallel arrangements of drive coils to accommodate different RPM and supply voltages, i.e. all coils in parallel to make a low value of inductance which will give fast response at low voltages, or all coils in series to give a high inductance which would need a high voltage supply but at lower current draw.

Some tests

Here are a few scope traces to illustrate some of these ideas. My test unit has 8 poles using 3/4" Neo disc magnets, 8 coils in parallel using iron powder cores giving 1.2mH total, and a variable supply of up to 14 volts DC, which was the basis for the evaluation of the rule given above. At low speed, the voltage at the SiC switch (yellow), and the current through the coils (blue) looks like this:



Note that the current wave form, peaking at about 7 amps (70mV from the current probe), is starting to become asymmetric with respect to the charge and discharge slopes. This is due to the field around the inductor now being modified by the movement of the magnet, as dictated by Lenz's Law. That means that some of the current invested in making the rotor spin can not be recovered in the discharge pulse to the battery. Also, the voltage at the switch when it is off now varies with the induction of the magnet, as shown in the second figure above. If the timing and length of the drive pulse is varied to produce a much higher RPM, the wave form looks like this:

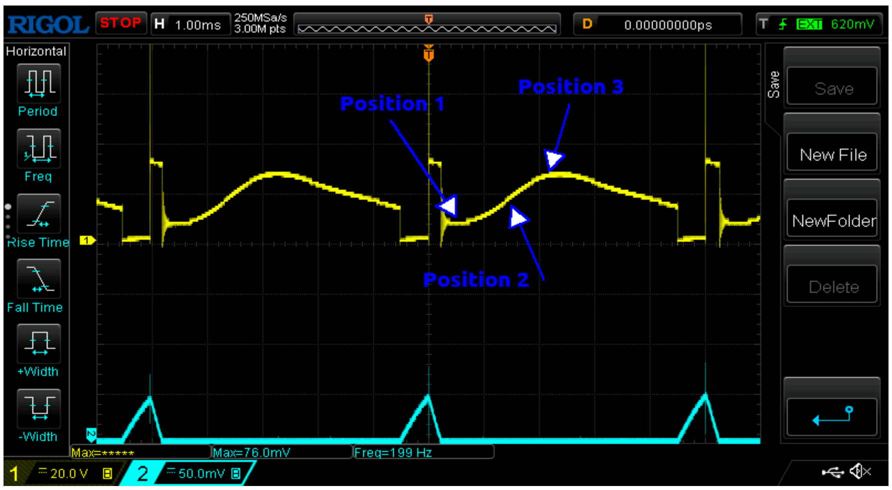


Now it is seen that almost all of the drive pulse energy is invested in turning the rotor, and only a small fraction is left over for the recovery pulse. Also, note the small lump in the current wave from just before the switch turns on, and the flat top of the induction curve. This is due to the induction in the drive coil making a voltage high enough that it back feeds through the body diode of the FET switch, into the run battery, and creates charging current just as a conventional generator would. This has the undesirable consequence of back torque. Both of these factors indicate that this RPM is too high for this motor design. Either the supply voltage can be raised but keeping the same rpm through timing adjustment, or the RPM can be lowered, again through timing adjustment. There is a large field for experimenting with different settings, and these will be different for each experimenter's setup.

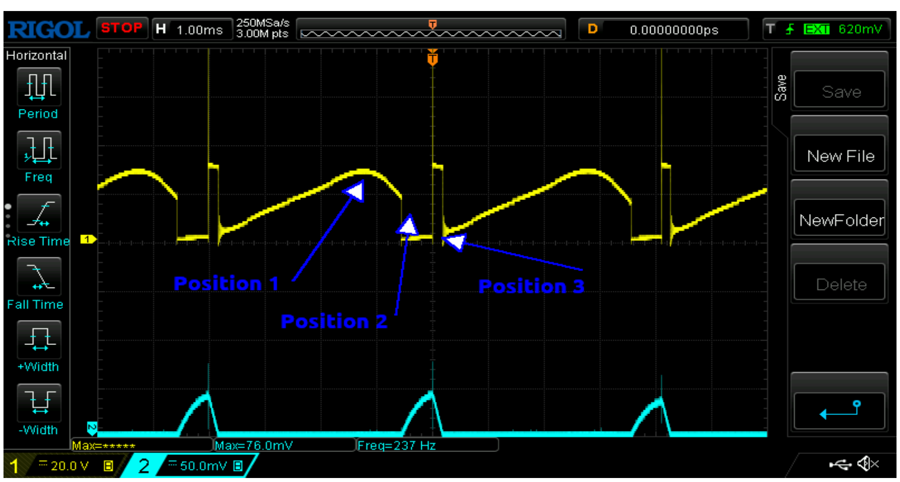
In the above trace, it can be seen that while the rotor is turning faster than in the previous, giving more pulses per second, the peak amperage is lower, while the total current drawn by the motor is close to the same in both cases. The cause for that reduction in current is what is called "degradation of potential" in motor theory. It in essence means that due to the moving magnet the effective value of the inductor has in essence increased such that the power supply can not ramp up the current as before. The timing and width of the pulse in relation to the magnet position will make for a very wide range effects of this nature. For example, for a given timing, increasing pulse width will generally make for increased RPM, but a point is reached where the pulse width becomes too long and is counterproductive by interacting with wrong polarity, i.e. where the pull turns into push, or vice versa.

Attraction and repulsion

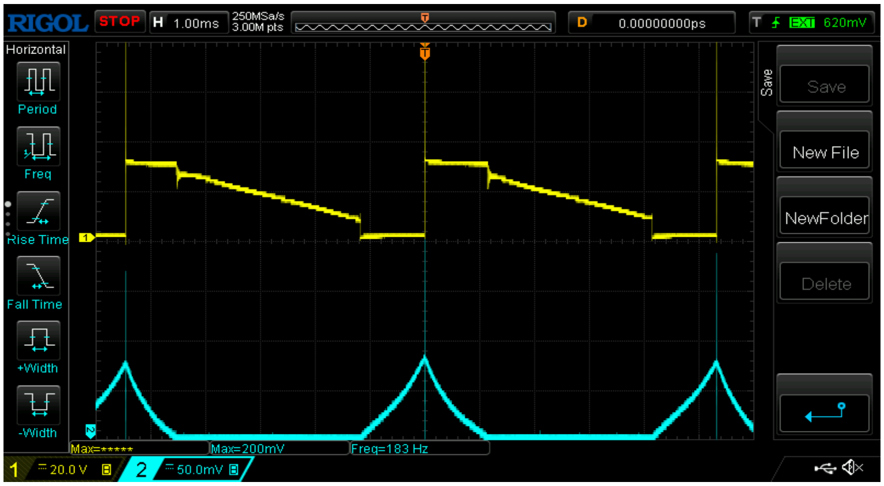
As for the two modes, attraction vs. repulsion, I have not at this point decided that one is necessarily better than the other, as the timings can be tweaked for about the same performance. For clarity here is a trace from the attraction mode with the positions indicated as before:



This shows the motor pulse of 500uS and the recovery pulse of about 200uS occurring just before position 1. This is just one of many settings that I made while experimenting, not to be seen as optimum, but a search for best combination of high RPM, low current draw, and length of recovery pulse. Again, highest RPM is not the best for these motors. Here is a similar circumstance now in repulsion mode:



Again, this is not an optimal condition as the recovery pulse is still being limited by the proximity of the magnet as it departs. A longer pulse time starting farther from position 3 would require more drive current, but as the recovery pulse would then be occurring in the midpoint between magnets, assuming sufficient spacing, it would not be as affected by the changing field and not be attenuated to the same degree. This is definitely a rich palette for testing and experimenting. As a final example, here is a trace showing a wide pulse width timed to be slightly in attraction mode, but with the recovery pulse making for some drag. This shows that it is possible to get a good percentage of recovery pulse into the battery loop, but at the cost of increased motor current:



Summary recommendations

My efforts in testing these types of motors has been guided by a preference towards that which is practical, economical, and readily replicated. Perhaps this is a bit like the old "drunk looking under the street light" joke, but if there is to be some sort of grass roots energy device that becomes open source, it should not entail large quantities of copper, massive or expensive battery banks, very high RPMs, or other extremes. Whatever additional, esoteric, and as yet unknown factors may need to be taken into account in order to elicit anomalous battery recharging behavior on a reliable and consistent basis, the more mundane considerations described in this article will nevertheless still be encountered. From what has seen on the bench and in the presentations by others, here are some suggestions to further ongoing efforts:

* The switched inductance used in pulsed magnetic motors as discussed here must meet several criterion: sufficient windings to create magnetic force, proportional to ampere-turns, but with low resistance to avoid loss. The inductance must be low enough to be switched quickly to allow for sufficient pulses per second. It appears that somewhere in the hundreds of pulses per second range is desirable. From all the variations encountered so far, the average total inductance switched at the FET is (speculatively) going to be near the range of 1mH to 5mH.

*Inductors with cores concentrate the magnetic fields to a small aperture, and can give results at lower voltages. A disc shaped rotor is indicated here. Core material should be something made for the purpose, i.e. low loss. Iron powder or ferrites made to be resistant to saturation are preferable, in my opinion, to the welding rod cores often suggested. Magnets used in this context do not need to have a very high flux rating. High value Neo magnets can make for troublesome cogging effects, which can be mitigated with a heavy rotor and wider coil-magnet spacing. Also, the high flux levels of Neo magnets will cause higher induction when the switch is off, such that unwanted back feeding of current through the FET body diode will occur at low RPM, as explained above.

*Air core inductors have some advantages, as they have no core loss, but that is balanced against low inductance and/or high resistance. They need to be made with a large aperture and a large magnet array in order to have sufficient force production. In contrast to disc shaped rotors, air core inductance needs longer cylindrical rotors. The higher resistance will necessitate a higher voltage supply. The use of Neo magnets is possible, as magnetic cogging will not be an issue. (For example, I have made a small window motor that operated on 130VDC @15mA using large Neo magnets.)

*As mentioned, rotors can have form factors that vary from wide and thin with many poles (the bicycle wheel SG), to long and narrow with 2 poles (Newman's later motors). Mike Clark's unit has a rotor in the mid point of this range, with 6 poles and a diameter close to its length. The larger radius rotors will have a good possibility to make torque, but will require very careful construction to rotate at high RPM. The smaller diameter rotors can easily be made to spin at high RPM. Spacing of the magnets is a factor of desired RPM, and faster rates need more spacing. The bicycle wheel rotors use 1 inch wide magnets with 3 inch spacing. I have used a bit wider spacing, 3/4 inch magnet and 3 inch space, in a small 8 pole rotor. In any case, the definitive test of proper spacing is to speed the rotor up to the target RPM (by using a hand drill) and look at the induction curve, as shown in the second diagram above. The curve should show an almost flat line when the magnets are in the space between the coils. A small bit of slope is OK, but significant slope indicates that the pole overlap is going to reduce torque generation to some degree.

*While much attention has been given to pulse charging effects in lead acid batteries, no one has mentioned **pulse discharging** effects. I would expect some sort of phenomenon of this nature, perhaps detrimental, given that these pulse machines draw a pulsing current from the run battery. It is something to keep in mind, as some researchers have used a large capacitor at the input in order to filter out these current pulses, without much mention of impact one way or the other. Since there are advantages to running these motors on higher voltages, there is an opportunity to use one of the many small DC-DC up converters available on eBay to power the motor. One can then stay with low voltage battery banks on the run and charge side. Using this method would also filter out any possible pulse discharge effect.

*Accuracy is important. It is a good idea to use a magnetometer to check all the magnets, selecting for those with the closest flux levels, and to use an inductance meter to trim all coils to the same value. Otherwise, one finds that there will quite a bit of jitter and variation in the scope trace due to the mismatch of the poles. It is also a good idea to make the coil to magnet spacing variable, as it will be found that with cored coils, the closest possible spacing is not necessarily preferable. Air core coils need to be wound such that the longer windings are stable and not subject to mechanical vibrations due to the magnetic pulsing. Due to the lack of magnetic cogging, close spacing is preferred.

*One very instructive technique to see pulse timing in detail is to trigger an LED strobe with the same signal that drives the switch. A small dot of appropriate color on each magnet will allow one to see the actual angular positioning of each pulse as the rotor moves.

The forgoing is offered in the spirit of encouraging experimentation, and eventual success. Best luck to all who endeavor in these fields. This article will be updated from time to time as new results are available. It will be available from this location. Good luck!