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AN232

Low-Frequency Magnetic Transmitter Design

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INTRODUCTION

Low-frequency magnetic communications (LFMC) is a viable "wireless" communications alternative to traditional radio frequency (RF) or infrared communications. It is well suited for certain applications when considering some of the characteristics of the topology.

Some of the main advantages of using low-frequency magnetic communications are:

- Good field penetration capabilities – Can penetrate non-magnetic materials such as water, concrete, plastic, etc. (no line-of-sight required).
- Limited and precise control of range – This may be a disadvantage if long range is required, but for certain applications this is a big advantage where limited or fixed range is required. For example, it is useful in automotive communications, or invisible fence control such as required for pets or water safety around pools.
- Low-power designs are possible, especially on the receiver side. This factor makes LFMC very attractive for PKE (Passive Keyless Entry), where the key fob constantly "listens" for a valid car and the device needs to be powered by small lithium batteries with years of useful battery life. It is useful in TPM (Tire Pressure Monitoring) where the sensor is awakened by a low-frequency signal to preserve battery life.
- Low-frequency design techniques (i.e., relatively low-frequency compared to RF) allow the designer to use low-frequency analog tools and building blocks. The designer has the freedom to use regular op amps, comparators and a general-purpose oscilloscope.
- Energy transfer – It is possible to power a receiver from the magnetic field. A good example is RFID, or alternatively, a low-voltage back-up.
- Low cost – A low-cost transceiver can easily be implemented by adding a resonant tank (LC) to a microcontroller with a PWM and comparator.

ABOUT THIS APPLICATION NOTE

This application note covers some basic aspects to consider when designing the transmitter portion of a LFMC link, such as:

- A description of the components that comprise the LFMC link.
- Explanation of the magnetic basics and assumptions made in the application note.
- Calculating the generated field strength that is inversely proportional to the cube of the distance.
- A practical method for generating a magnetic field is to create a serial resonant tank circuit.
- Data transfer is, in turn, accomplished by amplitude modulation of the field.
- Basic data formats that can be used in this kind of application.
- A description of a typical drive circuitry to generate the LFMC field.

LFMC LINK COMPONENTS

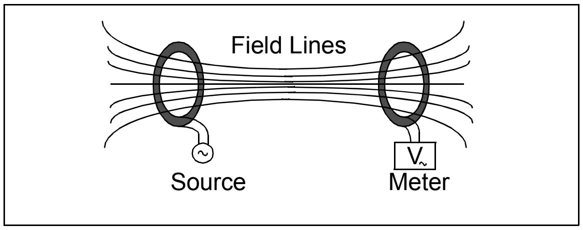
A LFMC link (see Figure 1) in its most basic form consists of a field generation source transmitter and a magnetic sensor that is sensitive to the generated field. Thus, there needs to be a field propagation path to "link" the transmitter and receiver. The propagating medium plays a major role in the performance of the communications link. It should be stressed that magnetic field behavior is not the same for electromagnetic waves normally associated with RF communications. Electromagnetic waves propagate for long distances in free space. The RF electromagnetic wave is, however, susceptible to scattering and distortion. Magnetic field lines, however, are less prone to distortion and known to penetrate water very well. A magnetic field does attenuate much more rapidly when compared to an electromagnetic wave.

This document focuses primarily on serial resonant tanks as a field transmission source. The tank consists of an air-coiled inductor and capacitor. Signal detection is typically accomplished with a parallel resonant tank.

To increase sensitivity, one ensures that the transmitter (TX) tank and receiver (RX) tank resonant frequencies are the same as the desired magnetic field frequency.

Another aspect to bear in mind is that sensitivity is dependant on the angle between coil face and the field lines. Maximum response is obtained when the lines pass through the coil perpendicularly, as shown in Figure 1.

FIGURE 1: ALIGNMENT OF FIELD LINES WITH COIL FACES



The TX and RX coils can be thought of as a weakly-coupled transformer, across which data may be transmitted by modulating the source (or transmitter) and detecting the modulated signal at the receiver.

MAGNETISM BASICS

It is important to note the difference between a magnetic field/electric field versus an electromagnetic wave. A **magnetic** field is a result of electrical charge in motion, or a magnetic dipole. One also only gets magnetic dipoles and not monopoles, as is the case for electrical particles. A magnetic field can, therefore, be represented by field lines that form continuous loops that never cross each other.

Electric fields, on the other hand, are the result of a distributed electrical charge. What both magnetic and electric fields share in common is that the field strength of both fields attenuates at a rate of $1/r^3$ when the source geometry is assumed to be a point source. What this means is that the field intensity at a distance 2X away from the source is 1/8th of the field intensity measured at a distance X from the source.

However, an electromagnetic wave reacts quite differently than the magnetic or electric field. Assuming the same point source, the electromagnetic wave propagates with a decay rate of 1/r. Thus, at a distance of 2X from the point source, the field intensity is only 1/2 compared to that measured at a distance of X from the source. This means that a magnetic field decays much more rapidly than an electromagnetic wave.

The magnetic field energy can be thought of as a cloud of energy packed around the source. On the other hand, one can imagine an RF wave as a sphere radiating outward from the source at the speed of light, with the wave energy spread out across the outer surface of the sphere.

The question then is; what is the link between magnetic/electric fields and electromagnetic waves?

To find the answer, we need to consider some properties of both magnetic and electric fields. The first is that a time-varying electric field induces a magnetic field and, conversely, that a time-varying magnetic field induces an electric field. These are special cases of Ampere's and Faraday's laws, respectively. Therefore, a time-varying field of either kind induces and reinforces a field of the other kind.

If the signal wavelength (magnetic or electric) approaches the dimension of the antenna, the magnetic electric reinforcement becomes strong enough to allow for electromagnetic wave propagation. For an antenna that is very small compared to the signal wavelength, one does not have an efficient propagating wave decaying at 1/r; instead, one has an attenuating field that falls off at $1/r.^3$

The effect, however, is negligible if the antenna dimensions are small relative to the wavelength of the exciting signal. The wavelength of a signal can be calculated using Equation 1, and at 125 kHz, is a long length of 2.4 km!

EQUATION 1:

$$\lambda = \frac{c}{f} \text{ [meters]}$$
$$c = 3 \times 10^8 \text{ m/s}$$

An antenna approaching this dimension is impractical, but at 500 MHz the wavelength is only 60 cm.

Higher frequency antenna dimensions are thus much more practical and a true propagating wave is easily realizable.

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Note:	For LFMC, a small component of the total energy is in the form of an electromagnetic wave, but that is negligible compared to the magnetic energy of a 125 kHz magnetic antenna.

Calculating The Magnetic Field Strength

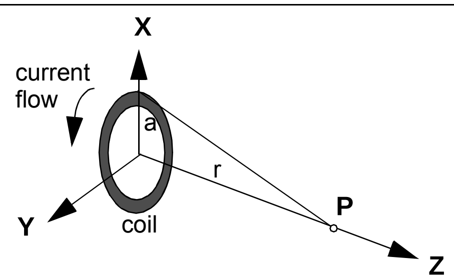
For most LFMC applications when calculating field strength, a magnetic field is generated by a base station by setting up an oscillatory current in a series RLC network at a typical resonant frequency of 125 kHz. The current passing through the inductor creates a surrounding magnetic field according to Ampere's Law. Using Equation 2, one can calculate the absolute magnetic field strength B at a point P from the radiating coil, as shown in Figure 2.

EQUATION 2:

$$B = \frac{\mu_o I N a^2}{2(a^2 + r^2)^{3/2}} \approx \frac{\mu_o I N a^2}{2r^3} \quad [Tesla]$$

where
μ_O = magnetic permeability
I = Current [A]
N = Number of turns
a = radius of coil [m]
r = distance from coil [m]

FIGURE 2: CALCULATING MAGNETIC FIELD STRENGTH



Note: For r >> a, the field strength falls of with $1/r^3$.

The field strength is therefore proportional to the:

- Number of turns (N)
- Current (I)
- Area of the loop (a^2)

As one moves away from the source with r>>a, the simplified equation again shows the characteristic $1/r^3$ attenuation. For practical reasons, the designer may prefer to use the voltage of the inductor (V_L) to calculate the field strength using Equation 3.

EQUATION 3:

$$|B| \approx \frac{V_L a}{2\omega_o \pi N}\left(\frac{1}{r^3}\right)$$

where

ω_O = frequency in [Rad/s]

$\omega = 2\pi f$

with $L \approx N^2 \mu_O \pi a$

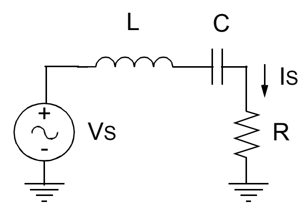
for r>>a

From Equation 3 with a given coil voltage at some distance from the coil, one now finds that B is inversely proportional to N. This is due to the fact that the current increases at the rate of $1/N^2$ with a given coil voltage. Only the case of an air-coiled inductor has been described, but one can use a ferrite-cored inductor as well. Adding a core has the effect of increasing the effective surface area, enabling one to reduce the physical size of the coil.

Serial Resonance

A typical serial resonant tank circuit is shown in Figure 3.

FIGURE 3: SERIAL RESONANT TANK CIRCUIT



The formulas for calculating serial resonant tank values are shown in Equation 4.

EQUATION 4:

$$2\pi \cdot F_0 = \frac{1}{\sqrt{LC}} = \omega_0 \quad \text{(a)}$$

$$I_{\max} = Vs / R \quad \text{(b)}$$

$$V_{L\max} = V_{C\max} = Q \cdot Vs \quad \text{(c)}$$

$$Q = \frac{\omega_0}{\beta} = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR} \quad \text{(d)}$$

$$\beta = \omega_2 - \omega_1 = R / L \quad \text{(e)}$$

Note that *R* represents all losses such as resistive, magnetic, etc. A short description of each equation given above is as follows:

(a) Used to calculate the resonant frequency of the tank.

(b) Gives the maximum serial current as a function of applied voltage (note this is not the same as inductor or capacitor current) and effective serial resistance.

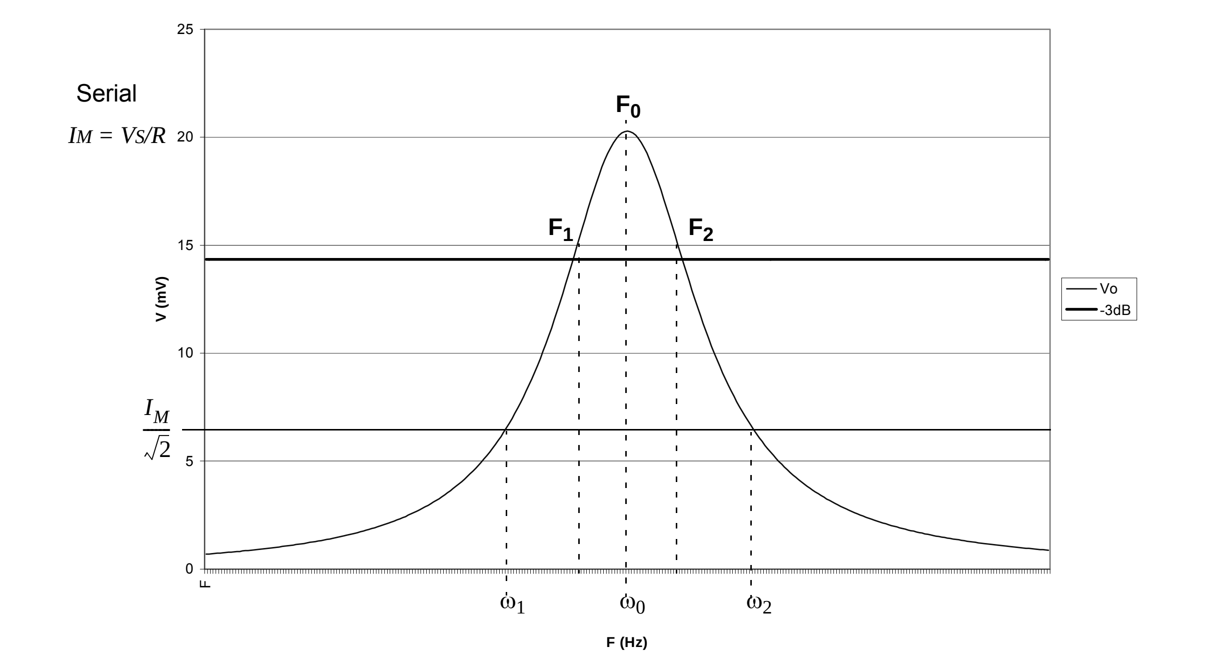
(c) Shows that the inductor and capacitor voltage is equal to *Q* times the source voltage at resonance.

(d) Shows all the various ways to calculate the Quality Factor (*Q*) of the tank circuit.

(e) Used to calculate the 3 dB bandwidth.

Figure 4 shows the frequency response curve for a typical serial resonant tank circuit.

FIGURE 4: FREQUENCY RESPONSE CURVE FOR RESONANT TANK CIRCUIT



MANUFACTURING TOLERANCES

A good rule of thumb is to stay within the -3 dB limits, giving component tolerances by Equation 5.

EQUATION 5:

$$Q \leq \frac{1}{T_{cap} + T_{ind}}$$

TCAP and TIND are the individual manufacturing tolerances for capacitance and inductance. For 2% parts, a *Q* of 20 works very well. Lower tolerance components may be used at the expense of sensitivity, and thus yielding a lower range. The corresponding final design must accommodate a wider bandwidth and will, therefore, have a lower response.

Data Formats

In designing a LFMC system, one has the choice of implementing any one of a large variety of modulation formats. On-Off Keying (OOK) lends itself well to realizing a practical and reliable system. With OOK, the signal is modulated by simply turning the field generation source on and off, depending on a chosen data format.

An example of a half bridge drive systems dynamic response is shown in Figure 5. Figure 5 shows the typical response when turning a tank circuit on (i.e., applying a drive signal) and, after some time, switching the tank off again. It can be seen that the oscillations amplitude increases rapidly upon start-up. It then increases up to a maximum amplitude as predicted by Equation 4. There is some finite time required for the tank to start-up and reach the eventual maximum amplitude. There is similarly a finite time required for the tank oscillations to decrease to some desired level. The rise and fall times will be the predominant factors in choosing a baud rate. Other factors are more concerned with receiver design and choice of AGC (Automatic Gain Control) topology. LFte is the elemental period used in LF communication, and a practical value is 400 μs or longer.

The Manchester, PWM and PPM data formats are shown in Figure 6. Manchester has the advantage of having a constant duty cycle and more efficient data rate. PWM encoding, on the other hand, simplifies the receiver decoding and improves the bit error rate.

When designing an LFMC system, one should keep in mind that it will be exposed to noisy environments. It is a good idea to incorporate some error correction and detection scheme upon implementing a communication protocol.

FIGURE 5: DATA BIT RISE AND FALL TIMES

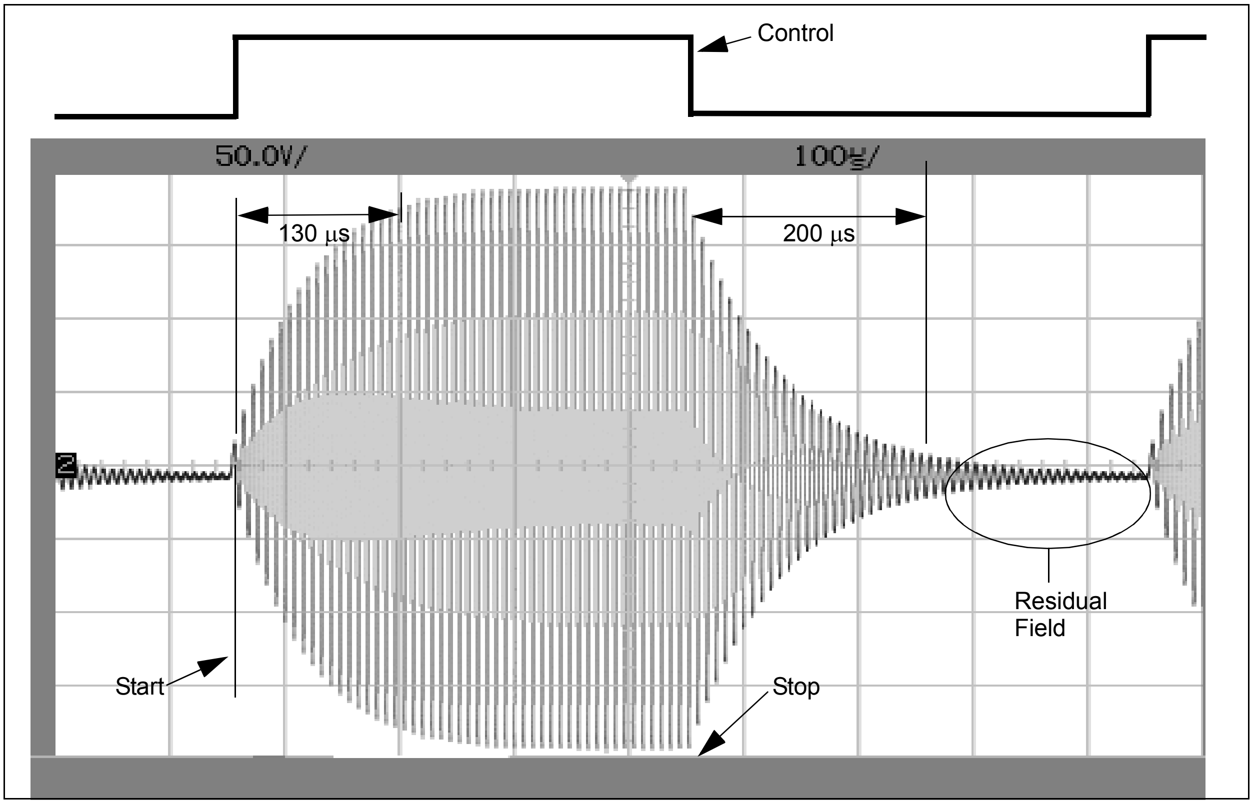
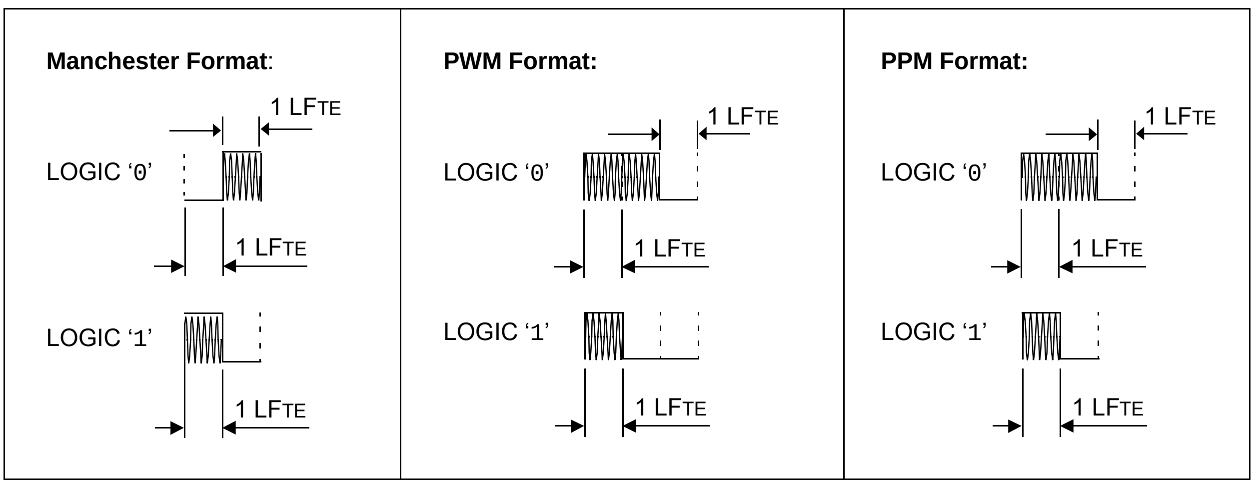


FIGURE 6: DATA MODULATION FORMATS

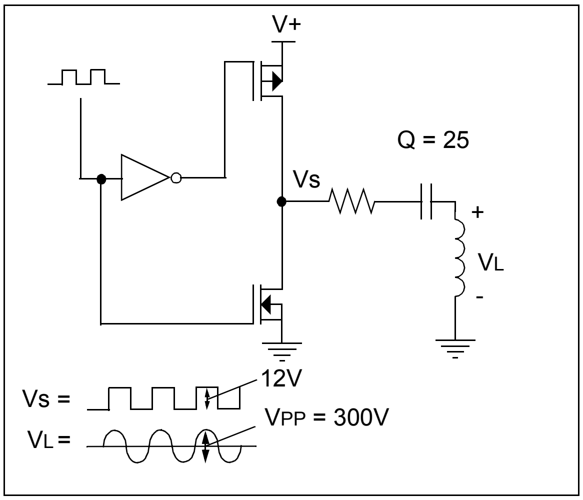


DRIVE CIRCUITRY

One of the most efficient methods to drive the resonant tank is a class-D drive circuit in either a Full or Half-Bridge mode. Figure 7 shows a typical half-bridge implementation. One gets very good results with a half bridge, and it has the advantage of being low cost and it is easy to implement.

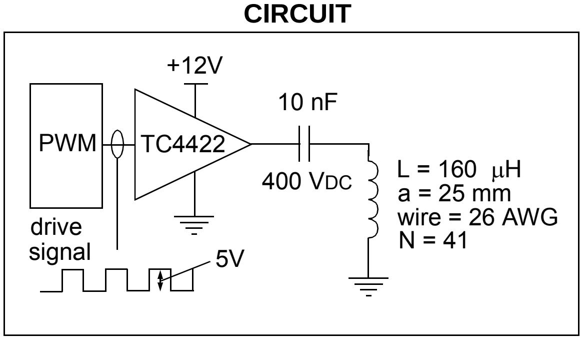
The use of a serial resonant tank circuit becomes clearer in this section. A high Q serial resonant circuit has its lowest impedance at resonance. The current passing through the antenna coil shown in Figure 7 consists mostly of the fundamental current component, although the drive circuit uses square wave excitation that has very high harmonic content.

FIGURE 7: SQUARE WAVE EXCITATION



A very economical and straightforward drive circuit can be realized with the circuit shown in Figure 8.

FIGURE 8: SIMPLIFIED DRIVE CIRCUIT



Microchip's high-current MOSFET drivers (such as TC4421/TC4422) are very suitable for this application. The device takes care of all the necessary level translations and deadband control, resulting in a very efficient and fast output, thereby reducing cost and losses. These devices have the added advantage that they can be directly driven from logic levels.

Be sure to use high quality capacitors with low tolerances (see 'Calculating the Bandwidth and Q' section on tolerances). A good choice is Panasonic polypropylene film capacitors – ECQO(µ) series, rated at either 400V or 600V as they reduce losses and are relatively stable over temperature variations.

The circuit shown in Figure 7 gives 135 VRMS out across the inductor and capacitor. It consumes 0.5 A_{RMS} at 12V with a constant output. This means that the average current consumption is typically 0.25 A_{RMS} for Manchester encoding.

The drive signal can be generated directly by the PWM unit on most PIC® microcontrollers such as a PIC16F627 microcontroller. For a device operating at 20 MHz, one can obtain a 125 kHz signal by setting the Timer2 prescaler to 1. A period of 8 µs is then obtained by setting the PR2 register to 39. To get a 50% duty cycle output, set CCPR1L to 14 and CCP1CON<5:4> to <0:0>. These settings will ensure a constant carrier. To modulate the data, one can turn the drive signal on and off by setting and clearing the CCP1RIL bit.

There are various transmission formats that can be used to transfer data, but keep the rise and fall times of the resonant tank in mind. The response for the circuit in Figure 8 is shown in Figure 5. The drive circuit was modulated on and off at 400 µs intervals.

Towards a Faster Response

The rise and fall times are limiting factors to shortening LFTE from a field generation perspective. In order to increase the baud rate, one needs to accelerate the turn-on and/or turn-off response. Figure 9 shows a modification of the basic circuit in Figure 7 to accomplish both a faster turn-on and turn-off time.

The basic bridge drive circuit shown earlier took about 130 µs to reach 90% of full-scale value. The start-up time can be decreased by starting the tank in Full-Bridge mode, then maintaining resonance in Half-Bridge mode, once full-scale is reached.

This concept can be implemented (see Figure 9) by using two FET drivers as the two halves of the full-bridge converter. The tank is started up by driving the two half-bridge drivers 180° out of phase. This effectively doubles the applied source voltage. As soon as the full-scale amplitude is reached, the other half-bridge driver is grounded. A circuit based on two TC442X FET drivers takes about 40 µs to reach full-scale. That is a significant speed increase compared to the 120 µs to reach 90% of full-scale for the standard half-bridge system. Herein lies a warning: if the resonant capacitor voltage rating is not at least double the half-bridge full-scale voltage swing, then care should be taken to ensure that Half-Bridge mode is engaged before the output voltage swing becomes too large. A good safety backup is to engage the half-bridge after 6 full-bridge cycles, irrespective of the output voltage.

Toward Faster Turn-Off

Figure 9 shows a turn-off acceleration circuit. A triac is used to discharge the resonant tank at turn-off. This circuit works instantaneously. The triac is typically fired at a voltage of zero, which reduces the EMI radiation.

The PWM bridge drive is in phase with the tank current if the tank is properly tuned. The tank current and voltage are 90 degrees out of phase. Figure 10 shows proper turn-off timing.

This turn-off clamp circuit also has the advantage that there is no residual field left after turn-off. This simplifies receiver design by reducing the receiver’s AGC functionality. A good receiver AGC is needed when operating close to a source that does not have a turn-off clamp. The AGC circuit needs to be able to distinguish between valid data and the residual field. If the receiver is unable to do so, it will interpret the field as being continuously high.

Note: The design examples shown in Figure 8, Figure 9, and Figure 10 have not been independently tested for conformance to FCC regulations.

FIGURE 9: MODIFICATION OF THE BASIC CIRCUIT

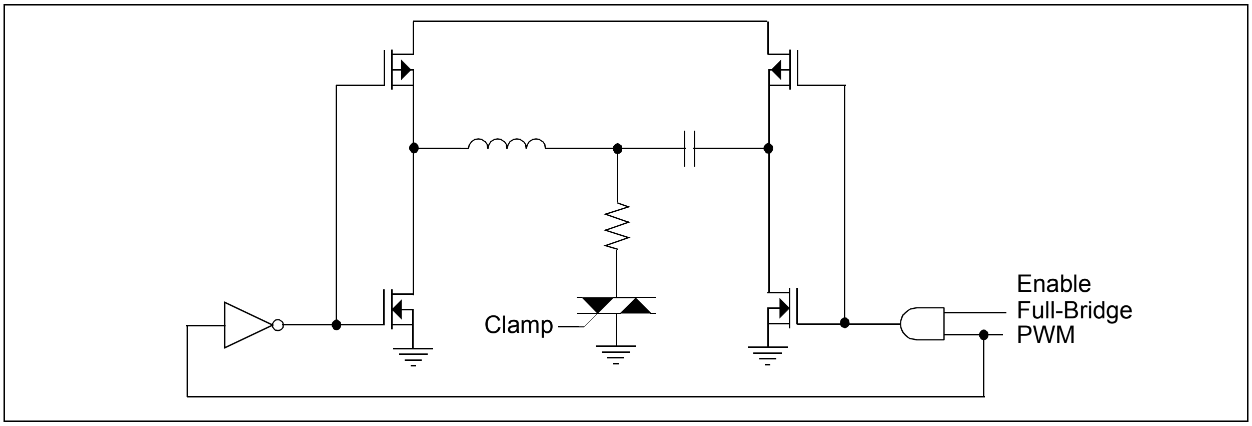
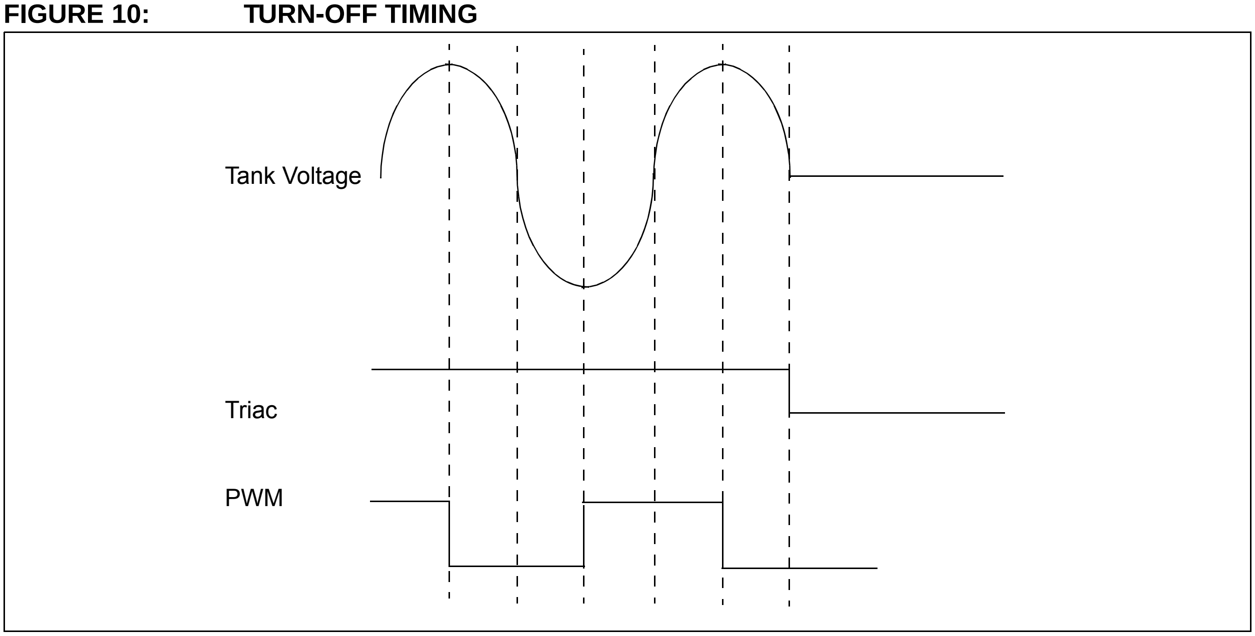


FIGURE 10: TURN-OFF TIMING



BASE STATION CIRCUIT DESCRIPTION

The drive circuitry (see Appendix A) consists of TC4422 (U2) and TC4421 (U3). U3 is an inverting FET driver and U2 is a non-inverting FET driver. U3 is the main half-bridge drive device and U2 is only used during start-up as explained previously. During the first 5 cycles of start-up, both U2 and U3 work in tandem as a full-bridge drive circuit. In Full-Bridge mode, U2 and U3 are driven from the PWM output via RB3. At this time, RB4 is defined as an input and thus has no influence on the input signal to U2.

The driver is converted to a half-bridge made after the 5 start-up cycles by driving point A to ground. This is done by changing RB4 from an input to a low-level (i.e., zero) output. This has no influence on the signal to U3, but it grounds U2. One can remove U2 and physically ground point A if a fast turn-on is not required. Removing U2 also increases the efficiency and output voltage slightly.

Turn-On Timing

Figure 11 shows the proper turn-on sequence referenced from the PWM output cycles.

Turn-Off Clamp

The turn-off clamp is realized by discharging the resonant tank through R1, R2 and a 600V rated triac Q1. Q1 is a Q6x3 surface mound triac from Teccor Electronics. The high tank voltages necessitate the need for two small serial resistors. Alternatively, one can use a single high-voltage resistor. A single PNP transistor, T1, forms a gated drive circuit and is activated by driving RB7 low. Refer to the previous section for timing requirements. The clamp circuit ensures that no residual energy is left in the tank, thus simplifying receiver design (this is not needed for LF_{TE}'s of 400 μs or more).

Power Supply

The circuit consumes roughly 0.5 A_{RMS} when transmitting continuously in Half-Bridge mode. It consumes approximately double that amount of current during the 40 μs start-up. The average transmitting power consumption is 0.25 A_{RMS} for Manchester encoding. Instantaneous peak current is about 1.2 A. The overall current consumption when transmitting data continuously is roughly 3 Watts, but adequate tank capacitance is needed to supply the relatively high peak current and reduce supply ripple. C4 is the main smoothing capacitor. A Panasonic FC series 25V 560 μF is used because of its 1.2 A ripple current specification. C2 and C3 are local DC coupling capacitors for U2 and U3, and are 20V 0.68 μF tantilum capacitors.

Communications

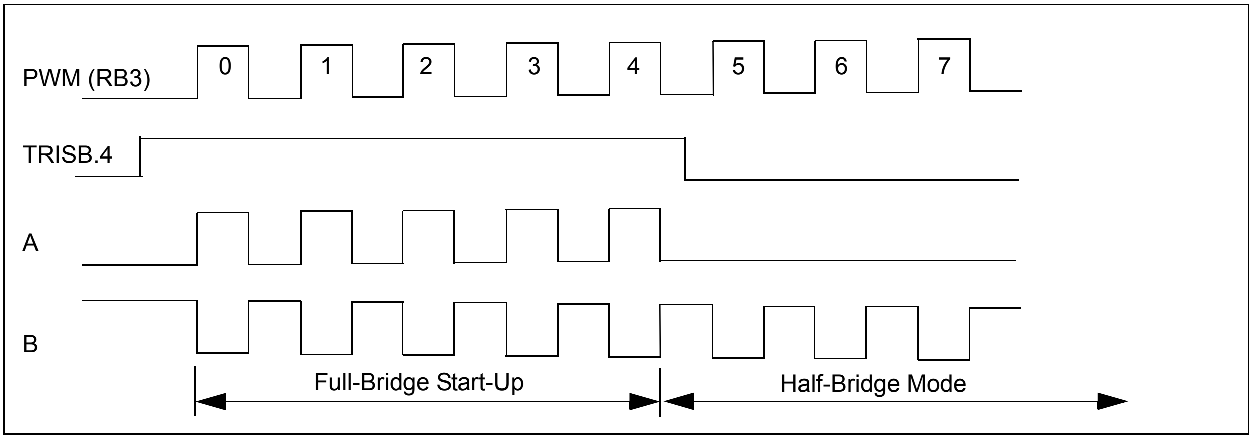
Serial communications is performed via the UART on the PIC16F628, and the voltage translation is done with a MAX232. Flow control using CTS and RTS is implemented on RB6 and RB5, respectively.

CONCLUSION

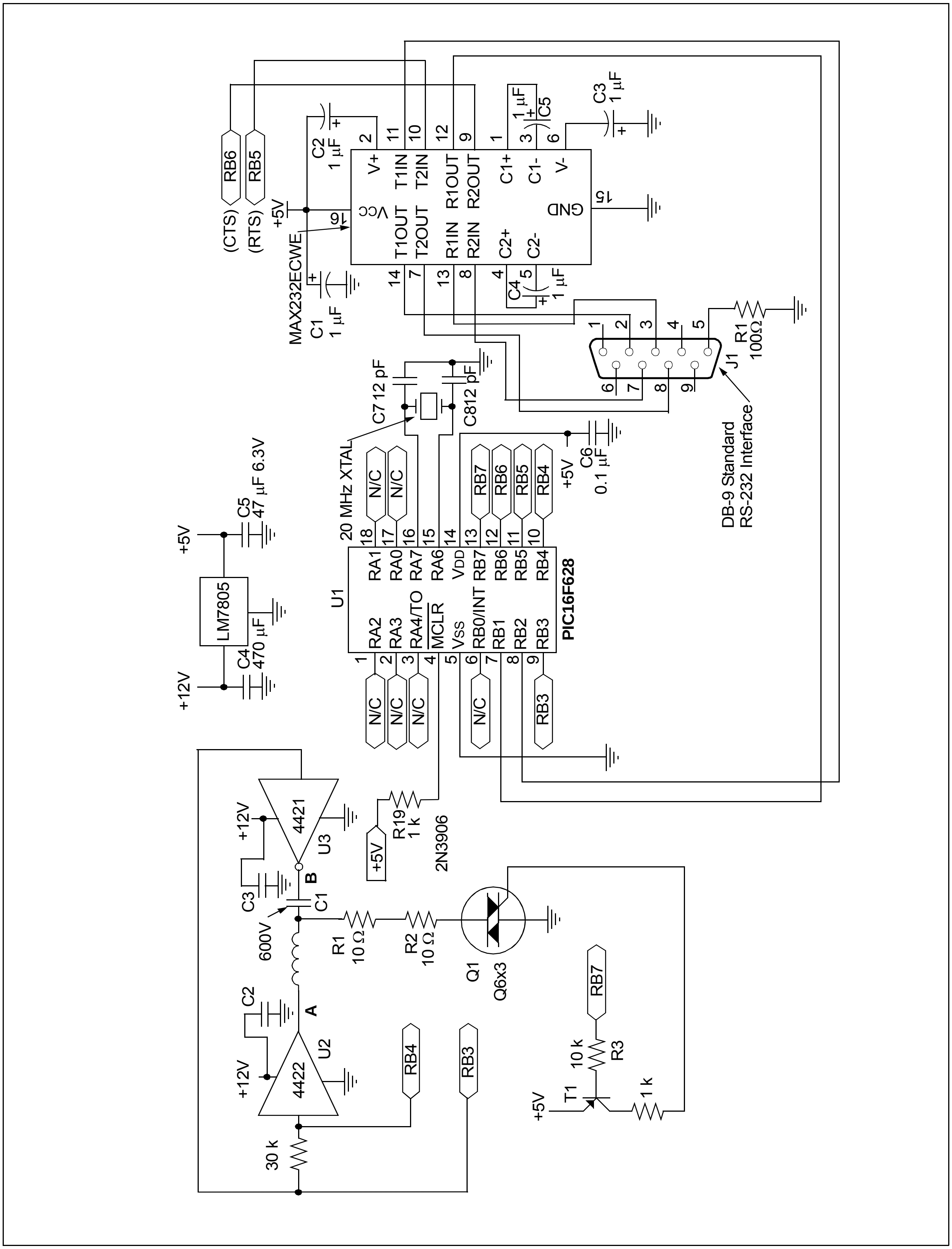
The choice of a PIC16F628 with a PWM lends itself towards an effective design of a low-frequency magnetic transmitter circuit. In addition, the TC4421/ TC4422's are well suited as FET driver for this type of application. The main advantages of using low-frequency magnetic transmitter design are:

- Good field penetration
- Precise range control
- Low-power consumption
- Overall low cost

FIGURE 11: TURN-ON TIMING



APPENDIX A: BASE STATION CIRCUIT



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