“Most adjustable frequency drives operate by using a bridge rectifier to convert the incoming AC voltage to DC voltage. An inverter in the drive then converts the DC voltage into a precise output voltage and frequency to control the speed of the motor.

Drives today use a diode bridge rectifier to convert the AC line power into a fixed-voltage DC bus. A DC bus capacitor bank is then used to filter out the AC ripple.

While this results in a very efficient drive, it can cause disturbances on the AC power line due to the way the drive draws AC current. Current cannot flow from the rectifier into the DC bus until the input voltage is greater than the DC bus voltage. This only happens for a very short period of time for each phase. This causes a non-sinusoidal current flow created by the input stage of the drive. In order to transfer the energy required by the motor in such a short period of time, the peak current must be high.

The input current is non-sinusoidal. It consists of two discrete pulses per half-period. Because the current pulses are centered in the voltage period, the displacement power factor is almost one. The result is that such a current waveform has a high level of harmonic distortion.

A second concern is interference with other equipment. The strength of the magnetic field that is built up around a wire is proportional to the pulse rate of current in the wire. These fast changing current pulses transmit a stronger electrical noise signal than a normal sinusoidal current. This can result in an audible hum in other equipment, unstable displays on monitors, unreliable data transmission, or interference with the operation of sensitive electronic equipment.”
Interference Description

• The EMI symptoms are characterized by continuous low frequency noise when the Evergreen IM motor is running at any speed.
  – The Evergreen IM is run at high-efficiency, constant-on low-speed mode continuously between heat calls for better air filtration and more even home temperatures.
  – The interference symptoms are worse when the motor is running at medium-high speed during the furnace call for heat.
  – The symptoms are worse when the motor is ramping up to a higher speed.

• The EMI is being radiated by the unshielded power lines within the walls of the home (Romex) and detected by both channels of a high-gain filtered lightning detection receiver operating in the VLF range.
  – Verified by reorienting the directional antennas to the AC power wiring within the walls of the residence.
  – The periodic EMI forces the Automatic Gain Control (AGC) of the receiver to adjust the gain downward, reducing the sensitivity of the system for the duration of the EMI bursts.
  – The noise is occasionally manifested as false signal detections as noise exceeds the signal detection thresholds.
Evergreen IM Installation

- The Evergreen IM is installed per recommendations in a 13-year old Heil NTC6150K 80% efficiency 120,000 BTU output forced-air furnace with a Honeywell ST9120 sequencer/control board.
  - The motor replaced the OEM ¾ HP PSC motor.
  - The motor is wired to operate at its highest 1 HP range.
  - The motor is wired to run at its MED-HI speed for heating, HI speed for cooling, and the high-efficiency low speed for continuous fan operation.
  - Proper heating speed operation was verified by comparing temperature rise before and after installation was within limits specified by Heil for the model.
  - Operation of the motor itself is perfect.
    - Objectives of lower operating noise, lower continuous fan operating cost, better air filtration and outside air exchange, and even home temperatures achieved.
Motor Installation with PFC Inductor

- PFC choke wired in series with motor continuous power hot lead from furnace controller.
- Common-mode snap-on ferrite EMI choke on motor power leads, 2 turns.
- Common-mode snap-on ferrite EMI choke on thermostat cable, 2 turns.
- PFC choke wired in series with motor continuous power hot lead from furnace controller.
Motor Installation with PFC Inductor

- PFC choke wired in series with motor continuous power hot lead from furnace controller
- Common-mode snap-on ferrite EMI choke on motor power leads, 2 turns
Motor Installation with PFC Inductor

- PFC choke wired in series with motor continuous power hot lead from furnace controller.
- Common-mode snap-on ferrite EMI choke on thermostat cable, 2 turns.
- Common-mode snap-on ferrite EMI choke on motor power leads, 2 turns.
Description of System Experiencing EMI

- System is an amateur home-built lightning detection and location receiver.
  - System description is at [http://www.blitzortung.org](http://www.blitzortung.org)
  - The system detects lightning with two electrostatically shielded, high-gain, un-tuned ferrite antennas positioned 90 degrees to one another, sensitive to the magnetic component (H-field) of distant lightning discharges.
  - Antennas feed a 2-channel adjustable-gain amplifier with pass band filtering optimized for VLF lightning detection.
  - The gain and detection threshold of the amplifier channels is adjusted by an AGC circuit that measure the noise floor between detection events.
  - A controller unit with two analog-to-digital converter channels (ADCs) measure the output of the amplifier, detect when pulses exceed thresholds, and timestamp the received signal with a high-accuracy, GPS-based time reference.
    - The detected pulses and timestamps are sent via the Internet to a central server where signals are correlated with signals from other stations to determine lightning location via Time of Arrival (TOA) triangulation methods.
  - Lightning strikes are detected when a detected lightning pulse exceeds the trigger threshold of one or both of the amplifier channels.
  - The system controller has the capability of displaying real-time oscilloscope-type plots of received signals for verification of noise and detected lightning waveforms.
  - The Harmonic Distortion EMI causes false lightning detections and forces periodic gain reduction of both channels, temporarily reducing overall system detection efficiency.
Antenna Description
Antenna Description

• Antenna elements are high-permeability (2000u), 250mmx7.5mm ferrite rods close-wound with 26 AWG magnet wire the length of the rod.
  — Antennas are designed for untuned operation in the 10 KHz – 150 KHz range, with flat response and no self-resonance or added tuning capacitors.

• Antenna elements are installed in PVC tubes with grounded, aluminum-foil electrostatic shielding to reduce near-field capacitively-coupled electrical noise
  — Longitudinal slit in shielding allows effective electrostatic shielding without reducing reception of far-field RF lightning signals.
    • No “shorted turn” that would block desired far-field RF signals as well as near-field electrical noise.
  — Shielding does not reduce near-field inductively coupled AC magnetic field noise sources.
  — Magnetic inductive near-field pickup of the harmonic distortion radiating from power lines in the house are the likely mode of EMI entering the system.
Antenna Frequency Response

- **Antenna in use**
- **Reference Antenna**
- **Self-resonance outside pass band of amplifier**

Graph details:
- 10dB/div
- Top: 6dBV
- Frequency range: 1kHz to 1MHz
- dV: 4.1dB
- f: 3.42kHz
Amplifier Description
Amplifier Description

- **Amplifier characteristics**
  - The inputs of the amplifier are terminated by damping resistors of 2.2k.
    - This leads to a more realistic current measurement for loop antennas and will reduce self-resonances.
  - Each of the two amplifier channels has four gain stages
    - The first and third stage of the amplifier are realized by programmable gain amplifiers that can be adjusted for a voltage gain between 1 and 32.
    - The second stage realizes a Bessel high-pass filter with a cut-off frequency of approximately 3kHz.
    - A passive Bessel low-pass filter with a cut-off frequency of approximately 50kHz is placed after this stage.
    - The last stage increases the voltage gain by a factor of 10.
    - The maximum overall gain of the amplifier is about 76dB.
  - **Linear pass band response of the amps is 3 KHz – 50 KHz, the desired range for distant lightning detection.**
    - 60 HZ power-line hum is effectively reduced
  - **The harmonic distortion components generated by the Evergreen IM at the peaks of the AC waveform that fall within the pass band of the amps can affect system AGC operation.**
Controller Description
Controller Description

- Based upon a 32-bit ARM Cortex-M4F micro-controller with a clock frequency of 168 MHz.
- The ARM Cortex-M4F micro-controller has three 12-bit analog-to-digital converters for conversion of the amplifier outputs.
  - These converters are capable of providing a throughput of up to 1,000 ksp = 1,000,000 samples per second.
- The controller provides AGC operation through the programmable op-amps of the amplifier first and third stages in response to noise floor measurements.
- The web-based interface to the controller can provide a real-time, free-running oscilloscope-type graph of the noise floor and noise sources.
Harmonic Distortion Waveform –
Before Installation of the PFC Inductor

With the furnace blower ECM motor running, this "wave" slides through the noise display every 10 seconds or so, forcing the noise floor higher and causing threshold to go higher with auto-threshold "on". Harmonic distortion on the AC line being detected by the N-S antenna?
Harmonic Distortion Waveform – After Installation of the PFC Inductor

After installation of the GE-supplied PFC choke, amplitude and waveform of the interference was unchanged. However, the EMI occurred far less frequently, solving the AGC problem.
Additional Tests

- The traces of the receiver software display were not sufficient to characterize the noise
  - ADC oscilloscope-like trace of the receiver software was perhaps missing some details due to sampling rate limitations.
  - I needed a way to sync to the AC line to be sure the noise source was, in fact, associated with line frequency disturbances.
- I connected an oscilloscope to the test output of one channel of the amplifier, after all of the gain stages and filtering
  - The oscilloscope synchronization was set internally to the AC line to allow sweeping the noise display through the entire AC cycle by adjusting the slope and level of the oscilloscope trigger controls.
  - Oscilloscope input set to AC coupling, vertical sensitivity set to a range sufficient to resolve normal background noise output of the amplifier and antennas.
  - The AC line trigger was set to positive slope and adjusted to bring the noise spike into range.
    - Noise always seemed to be at or near the + peak of the AC waveform.
    - Negative peak was not checked, but noise is likely there as well.
Without PFC Inductor Installed – Motor running at High Efficiency, Low Constant-On Speed, 1 HP

A constant high amplitude noise pulse was present at the same point in the AC cycle on the output of the amplifier. The pulse amplitude was above the normal noise floor and sufficient to cause false lightning detections and reduction of system sensitivity due to AGC action.
A constant, pronounced noise pulse was present at the same point in the AC cycle on the output of the amplifier. The pulse amplitude was slightly above the normal noise floor and insufficient to cause significant interference to the receiver.
Without PFC Inductor Installed – Motor running at MED-HI Speed during Heating Call, 1 HP

A constant, very high amplitude noise pulse was present at the same point in the AC cycle on the output of the amplifier. The pulse amplitude was greatly above the normal noise floor and sufficient to cause severe false lightning detections and reduction of system sensitivity due to AGC action.
With PFC Inductor Installed – Motor running at MED-HI Speed during Heating Call, 1 HP

A constant, very high amplitude noise pulse was present at the same point in the AC cycle on the output of the amplifier. The pulse amplitude was slightly above the normal noise floor and insufficient to cause false lightning detections and reduction of system sensitivity due to AGC action.
Observations and Summary

- Oscilloscope analysis of the receiver amplifier output confirmed that the noise source was due to harmonic distortion from the Evergreen IM.
  - Measurements taken after all gain stages and filtering of the receiver amplifier.
- Noise pulses were continuous during motor rotation at any speed or state.
- Noise pulses were synchronized to the same point of the AC power line cycle.
  - Observed near the peaks of the AC line
- Noise pulses were more severe under conditions of heavy motor load.
  - Motor ramping up to a higher speed.
  - Higher steady motor speed
- Without the choke, the pulses were passing through the receiver amplifier circuitry and causing severe performance degradation of the receiver.
  - The problem was much worse at higher motor operating speeds.
  - Problem manifests as false lightning detections on noise pulses and reduced receiver sensitivity due to AGC action of the receiver
- Propagation mode was through inductive radiation of the magnetic field induced from current pulses from the motor in the residential wiring.
  - Confirmed by changing orientation of directional ferrite antennas of receiver.
  - Noise was not being coupled through the power supply filtering of the affected receiver.
- The presumed cause of the current spikes was due to the nature of the internal Evergreen IM DC power supply driving the DC motor.
  - Current is drawn from the AC line only when the AC line voltage exceeds the voltage on the internal DC filter capacitor.
  - This occurs only on peaks in the AC waveform.
  - Non-sinusoidal current draw generates harmonics into the VLF range and within the pass band of the VLF receiver.
- The choke was very effective in attenuating the noise pulses at all motor operating speeds, keeping them mostly within the noise floor of the receiver and reducing the degradation of receiver performance.
  - The choke attenuated the current spikes from the motor by providing a current source during periods of high current draw by the motor.
- Common-mode ferrite “snap-on” chokes were installed on the motor power leads and thermostat cabling in the furnace cabinet with no effect on the VLF EMI.
  - The ferrite filters used are optimized for higher-frequency interference mitigation, likely accounting for the lack of effectiveness.