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SUBHARMONIC RIPPLE REDUCTION IN SCR-TYPE MAGNET POWER SUPPLIES

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SUMMARY

Subharmonic ripple in a magnet power supply output can cause unwanted low frequency field ripple in a magnet load. Among other things the ripple may be caused by SCR firing circuit imbalance. In critical applications, simply providing equally spaced SCR firing pulses, as is done in some all digital control schemes, may not be sufficient. This paper discusses in general the causes of subharmonic ripple and some approaches to the problem. A negative feedback scheme utilizing bandpass filters is analyzed and applied to a group of twelve phase .5MW power supplies. Results are given which show a substantial improvement in power supply voltage and magnet field ripple content at 60, 120, and 180 Hz. Application of the approach to other types of power supplies and limitations of the approach are discussed.

INTRODUCTION

Power supply subharmonic ripple in this paper means any significant ripple frequency in the power supply output which is below the fundamental output ripple frequency and above the power supply roll-off frequency. Generally, but not always, the subharmonic frequency is locked to and a multiple of the line frequency.

There are direct and indirect causes of subharmonic ripple (SHR). The major direct causes are the following:

1. Poor firing circuit balance.
2. Power line imbalance which includes modulation of the line by other sources at frequencies such as 15 or 30 Hz.
3. Either amplitude or phase imbalance in multiphase transformers.
4. Variations in hard fire gate circuit delay times.

An indirect cause of SHR is restricted power supply feedback bandwidth or no feedback at all to reduce the problem harmonics. The subharmonics are a problem for several reasons. One is that small amounts of subharmonic voltage ripple often cause large current and field ripples since the magnet load is primarily inductive and the subharmonic is generally low in frequency. And secondly, the SHR is often worst at a particularly undesirable power supply operating region, such as minimum output where a low energy beam is very sensitive to ripple.

Several different approaches can be taken either independently or with another approach to reduce SHR. One is to improve the SCR firing circuit balance. There is a limit, however, as to what is practical or what is even necessary. For even with perfectly equal spaced gate pulses, as can be obtained with some firing circuit systems, subharmonics can still be present in the power supply output due to line or transformer imbalances. Furthermore changing all the firing circuits for a multiphase power supply may require considerable work. Another approach is to build passive load filters to remove the SHR. Generally these filters must have low roll-off frequencies to be effective and as a result are very expensive for higher power applications. A third solution is to widen the bandwidth of the power supply's voltage feedback circuit. Widening the bandwidth can be effective for low frequency subharmonics but may not be practical for frequencies at or above 60 Hz since unstable operation may result. A fourth solution is to add parallel, high Q, tuned feedback circuits which are adjusted to the problem subharmonics. The tuned feedback circuits provide sufficient gain to reduce the subharmonics yet roll-off fast enough so that associated phase shifts do not lead to unstable power supply operation. The latter solution is the basis for the remainder of this paper.

TUNED FEEDBACK NETWORKS

Generally the subharmonics in the power supply output can be corrected by making small adjustments in the power supply's SCR firing angles. Normally only a few subharmonics cause problems (usually 60 and 120 Hz). These frequencies in the output are sensed with tuned circuits and fed back into the firing circuit input to adjust the SCR firing angles and cancel the subharmonics. Figure 1 explains the feedback more clearly. A power supply may already have one or more feedback circuits for voltage and or current regulation. The bandwidth of these circuits is generally not wide enough to attenuate the SHR and can be neglected for the present time. Figure 1a shows in solid lines the SCR controlled power supply from the analog input to the firing circuits to the power supply output. Notice that SHR caused either by firing circuits, or line, or transformer imbalances is represented by an independent input summed with the SCR converter output. The tuned feedback network to be added is shown dashed in Figure 1a. The feedback network contains narrow bandpass filters tuned to the frequency of the SHR to be removed. Figure 1b simplifies the power supply representation. Assuming that the voltage input to the firing circuit is a constant (contains no SHR ripple), the network

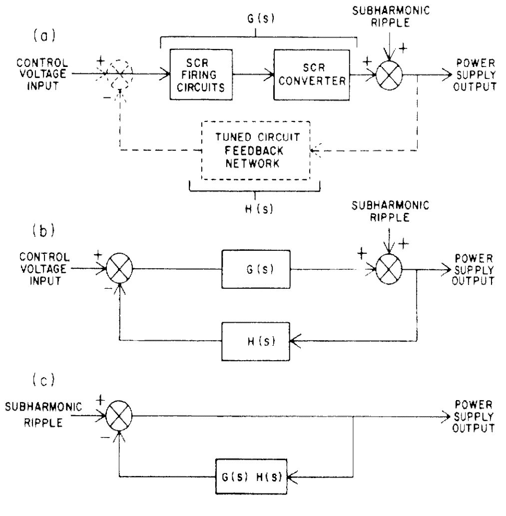

Figure 1 - Subharmonic Ripple Representation and Feedback Network

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can be reduced to Figure 1c for further analysis. From Figure 1c, SHR attenuation is given by equation 1.

$$\frac{V_0}{V_{ripple}} = \frac{1}{1 + G(s)\ H(s)} \qquad (1)$$

At the SHR frequencies, ripple is attenuated by a factor equal to the gain product, G(s) H(s). For the feedback loop to be stable, G(s) H(s) must meet conventional gain and phase roll-off requirements. The feedback loop can be analyzed by Bode plots. For the present time assume that G(s) has a constant value and no phase shift at the subharmonics of interest. If H(s) always has a phase shift less than or equal to ±90° then the feedback loop is always stable with good phase margin. H(s) can be implemented as shown in Figure 2a. The bandpass filters used in this paper are of the Negative-Immitance Converter (NIC) type although other types can also be used. Figures 2b and c show typical gain and phase shift plots for a three subharmonic NIC bandpass feedback network. The Q of each tuned circuit is set to about 30. Construction details of the NIC bandpass filter is given in reference 1.

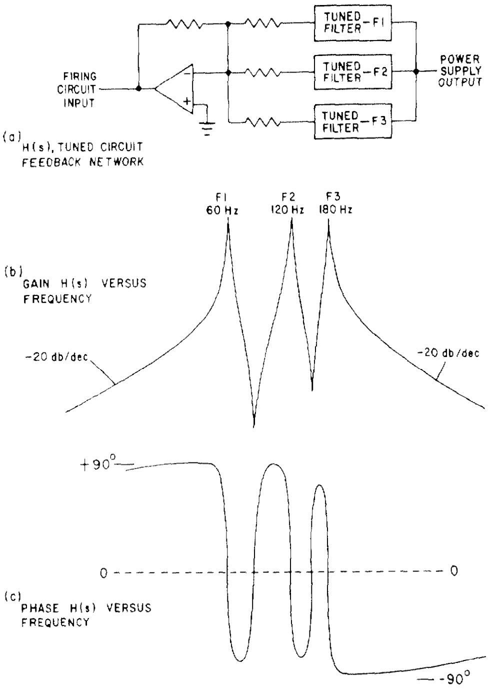

Figure 2 - Feedback Characteristics

In practice the previous assumption for G(s) does not hold at all frequencies of interest. At some frequency G(s) is no longer constant either due to the particular firing circuit employed, the sampling nature of the SCR converter, or the power circuitry used in the SCR converter. Further explaination is necessary. In one test, a low power twelve phase, star-connected SCR converter was built using linear ramp and comparator-type firing circuits which have excellent frequency characteristics. In measuring G(s) from DC to 240 Hz no appreciable phase shift was measured as would be expected from consideration of the sampling nature of the SCR converter. When the same firing circuits were put into a .5MW, 12φ power supply with interphase transformers, phase shifts of -12°, -24°, and -35° were measured at 60, 120, and 180 Hz respectively at one operating point. The phase shifts are attributed to phase overlap and interaction of the interphase transformers. As another example, firing circuit characteristics may be far from ideal. Firing circuits manufacturered by Vectrol Inc. have a very sharp roll-off characteristic at about 60 Hz. These firing circuits cannot respond adequately to inputs above 60 Hz. Thus several factors amy cause G(s) to have a gain and phase characteristic which must be taken into account along with H(s) to determine the overall stability and ripple reduction capability of the tuned feedback circuits. One way to be sure of G(s) is to measure the power supply output versus firing circuit input over the frequency range of interest, being very careful of any phase shifts associated with the output measurement circuits. Then G(s) can be plotted with H(s) on a Bode diagram and gain and phase margins evaluated. Ripple reduction using tuned feedback networks can then be predicited.

APPLICATION TO TRANSREX POWER SUPPLIES

The negative feedback technique with bandpass filters has been tried with success on several types of power supplies. Only the results of application to one type of power supply, a twelve phase, 5000A, 100V, are described herein. The application is used to demonstrate the technique and is not necessarily the only solution to the problem. The Transrex power supplies at Fermilab have large amounts of SHR due to poor firing circuit balance. The problem is particularly bad when operation over a wide voltage range is required since the percentage of SHR is largest at low output voltage. A spectrum analysis of the power supply output showed that the major subharmonic components were 60, 120, and 180 Hz. The Transrex supply already had a voltage feedback circuit. Examination of the voltage feedback circuit showed that it did not have sufficient bandwidth to reduce the problem subharmonics. The open loop unity gain point of the voltage loop occured at about 10 Hz. Thus ripple above 10 Hz could not be attenuated. The voltage loop bandwidth could not be widened enough to reduce SHR with-

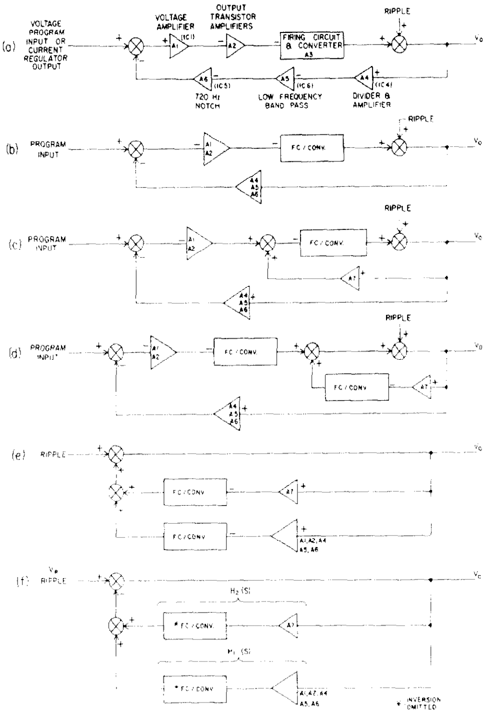

Figure 3 - Transrex Voltage Regulator Block Diagram

out causing stability problems. A block diagram of the voltage feedback loop is shown in Figure 3a and simplified in 3b. Figure 3c shows where the tuned feedback network (represented by A7) was added to remove the 60, 120, and 180 Hz ripple. The voltage regulator is further simplified in Figures 3d, 3e, and 3f. Figure 3f shows that for ripple attenuation, the tuned feedback circuits appear to be exactly in parallel with the voltage regulator feedback circuit. The main difference between the feedback loops is that the tuned circuits provide negative feedback at the subharmonic frequencies and the original feedback loop does not. The phase shifts reported in the previous section were used to calculate circuit stability and performance for this application.

EXPERIMENTAL RESULTS

A module called the Ripple Reduction Module (R^2 module) incorporating tuned feedback circuits was built which could be easily added to a Transrex power supply as shown in Figure 3c. The module was added to a number of power supplies in the Meson area at Fermilab with satisfactory results. Photos for operation of the power supply with and without the SHR feedback are shown in Figure 4. For these photos, the firing circuits were trimmed to give minimum SHR at 60V output. The top photograph shows operation of the power supply at 10V, the middle shows operation at 50V, and the bottom shows operation at 100V. In each photo, the top two waveforms show the magnetic field and power supply output ripple with the R^2 module off and the next two waveforms show operation with the R^2 module on. At 10V there is a strong 60 Hz ripple in the field and voltage output when the R^2 module is off. Firing circuit balance is so poor that two SCR's are not firing at all. With the R^2 module on, this SHR is substantially improved. Similar although less dramatic results are obtained for operation at 50 and 100V. The effect of the R^2 module being "ON" is to correct the firing circuit imbalance.

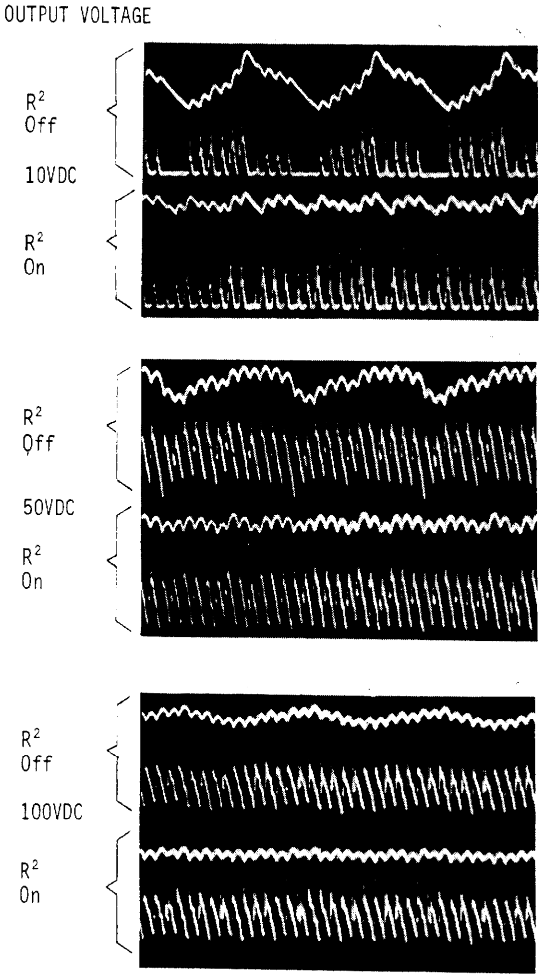

Figure 4 - Ripple Reduction Module Performance in Transrex Power Supplies

APPLICATIONS AND LIMITATIONS

The bandpass feedback circuits can be applied to many types of SCR controlled power supplies such as dual converters, cycloconverters[2], and conventional one or two quadrant supplies. The feedback technique works for frequencies other than multiples of the line frequency. For example 15 Hz modulation of the 60 power line by the Fermilab Booster accelerator can be removed from a power supply output by use of a bandpass feedback circuit. The SHR feedback circuit is easy to implement and often easy to add to existing power supply control circuits.

In order to use the bandpass circuits as described in these pages, the SCR firing circuit input should be an analog signal and the firing circuits should have a good frequency characteristic. For good operation, the firing circuits and power section should have a phase shift less than 45° at the subharmonics frequencies being attenuated. If a power supply is programmed to produce a step response the tuned feedback circuits can cause some ringing in the power supply output much like a tuned passive filter at the power supply output could cause. Application to a dual converter with circulating current is the only case observed thus far where ringing occurred in the output for a step input. Normally, power supply ramp rates are reasonable and overshoot is not a problem.

REFERENCES

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