PHASOR: A CONTROL COMPUTER METHOD FOR DISPLAYING AMPLITUDE AND PHASE OF RIPPLE COMPONENTS IN THE RING MAGNET VOLTAGE*

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Abstract

Deviations of 12-phase generator-transformer-rectifier systems from ideal performance result in the generation of ring magnet ripple at the fundamental and at low harmonics of the generator frequency. Analysis and display of the amplitude and phase of each of these harmonic components makes it possible for the systems engineer to minimize the ripple by readjusting the control system. The Zero Gradient Synchrotron (ZGS) control computer samples both the filtered voltage on the ring magnet and a reference voltage produced by a phase-lock loop connected to the generator bus. Data are taken during a selected interval of the ZGS cycle and are then analyzed. Computer driven graphic displays plot the raw ripple data, amplitude and phase bar graphs for each harmonic component, reconstructed ripple data for checking, and graphs for comparing ripple components under different operating conditions. Numerical information is also displayed. The PHASOR program corrects the phase angles for the phase shifts produced by the ZGS passive filter. These corrected angles indicate which of the 12-phase firing angles should be retarded or advanced to reduce the ripple.

Introduction

Power supplies for synchrotron ring magnets usually consist of phase-controlled rectifiers operated from an ac power line or from ac generators. The number of ac phases is often high to minimize the ripple. The ripple on the magnet is reduced even more in some systems by inserting a low-pass filter between the rectifiers and the ring magnet.

In a 12-phase system with a low-pass filter, the amplitude of the ripple component at the fundamental frequency of the power line may exceed the amplitude of the 12th harmonic. This is caused in part by the filter's attenuation being larger at the higher frequency. Additional causes include errors in the number of turns on the polyphase transformer windings, variation in the leakage inductance from one phase winding to another, lack of symmetry in circuit resistances, and imbalances between phases of the power line or generator.

The magnitude of the low frequency ripple components may be reduced on flattop by properly retarding or advancing the firing time of each of the 12-phase rectifiers with respect to the others.

Proper adjustment of the firing delays of each of the 12 phases is extremely difficult by trial and error methods and an optimum is difficult to determine by eye. For these reasons, analytical methods are required.

A swept frequency spectrum analyzer was used in an attempt to analyze the ripple during a 700 ms flattop of the ZGS ring magnet. At the low ripple frequencies, 50-600 Hz, the sweep rate for the required resolution was so low that an analysis could not be performed in the length of the flattop. In addition, no phase angle information is given by such an instrument.

The ZGS control computer system was used in conjunction with the program PHASOR to analyze the ripple and display the results. The program is of the interactive type where the computer operator directs the logic flow after observing the results of each section of the program.

Data Input

The reference for all phase angles was a square wave produced by a phase-lock loop that had one phase of the generator voltage as its input. This loop acted as a filter for the distortions in the generator voltage wave and gave sharp indications of corresponding points in each generator voltage cycle. The loop was adjusted so that the positive-going square wave transitions were at 90° on the generator voltage sine wave and were independent of generator voltage and frequency.

This square wave, shown in Fig. 1A, was the input to an analog integrator that was voltage limited at ± 10 V. The waveform from this is shown in Fig. 1B. The rise and fall times were adjusted to be slightly longer than the control computer data sampling interval. In this way, the computer was assured of one data point on the rise even through the computer was not synchronized to the generator.

The second input to the ZGS control computer data station was a voltage containing the magnet ripple information. It was obtained by capacitively coupling the voltage which was across one quadrant of the ring magnet to an amplifier with a high common mode rejection. Zener diode networks eliminated most of the dc component.

Data Taking

The manual keyboard at the computer driven scope was used to specify the point in the ZGS cycle for the start of data taking (e. g. 250 ms after the start of flattop). The keyboard was then used to enter the number of data samples of the ripple voltage that are to be taken. The computer then generates requisitions for all of the data points. Measurements are made at 100 μs intervals and alternate between the reference wave and the ripple wave.

When the operator pushes the DISPLAY NEW SET key, a new set of data is taken on the next ZGS cycle. These data are then displayed on the scope screen. Figure 3 top plots the samples taken on the reference wave. The points that are circled are on the rising and falling slopes of the reference. Figure 3 bottom plots the samples taken on the ripple wave.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

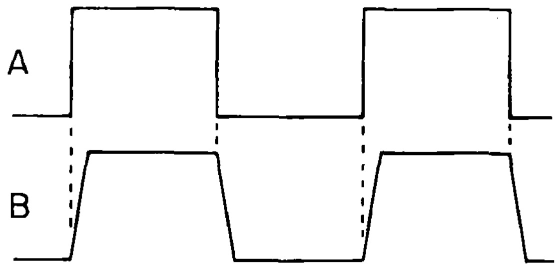


Fig. 1 Phase Lock Loop Waveforms

The computer operator, by inspection of the scope display, determines that the amplitude range of the data is acceptable and that enough points are taken. He may then proceed to analyze the data by pushing the ANALYZE button on the scope.

Analysis

A finite, periodic function V(t) may be written as

$$V(t) = \sum_{n} \left(A_n \cos n\omega t + B_n \sin n\omega t \right) \quad (1)$$

where

$$n = 0.\ 1,\ 2,\ 3 \ldots . \text{ and } \omega = \frac{2\pi}{\tau}$$

and the coefficients are given by

$$A_n = \frac{2}{\pi} \int_{-\frac{\tau}{2}}^{+\frac{\tau}{2}} V(t) \cos n\omega t \, dt \quad (2)$$

$$n = 0, 1, 2 \ldots .$$

$$B_n = \frac{2}{\pi} \int_{-\frac{\tau}{2}}^{+\frac{\tau}{2}} V_t \sin n\omega t \, dt$$

where $B_0 = 0$ and A_0 = twice the dc value of the signal.

If we make k measurements during one period of the function V(t), we may approximate the integrals (2) and (3) by the following:

$$a_r = \frac{2}{k} \sum_{d=1}^{k} V_d \cos (r\theta_d) \quad r = 0, 1, 2, 3 \ldots \quad (4)$$

$$b_r = \frac{2}{k} \sum_{d=1}^{k} V_c \sin (r\theta_d) \quad . \quad (5)$$

$$\text{Then } V(t) = \frac{1}{2} a_0 + a_1 \cos \omega t + a_2 \cos 2\omega t + \ldots + b_1 \sin \omega t + b_2 \sin 2\omega t + \ldots \quad (6)$$

or

$$V(t) = \frac{1}{2} a_0 + c_1 \sin (\omega t + x_1) + c_2 \sin (\omega t + x_2) + \ldots \quad (7)$$

where

$$c_r = \sqrt{a_r^2 + b_r^2} \text{ and } x_r = \arctan \left(\frac{b_r}{a_r} \right) \quad (8)$$

with the restriction $-180^{\circ} \leq x_r \leq +180^{\circ}$.

The first step in the analysis is to assign an angle θ_d to each of the data points. The computer searches the reference wave data points, Fig. 3 top, to locate all the positive-going edges. It counts the number of data points in each cycle and calculates the fractional intervals at the beginning and end of each cycle. These fractional intervals are calculated from the position of the circled points, Fig. 3 top. The total number of intervals is then divided into 360 to get the number of degrees per interval. θ_d for the first data point in each cycle and the frequency of each cycle are displayed on the scope screen. A value of θ_d for each data point is then assigned.

The computer uses the equations (4), (5), and (8) to compute the amplitude and phase of the first 12 harmonic components. The sums, equations (4) and (5), may be extended over more than one cycle if the operator so specifies.

The phase angles, x_r of equation (7), are then corrected for the phase shifts produced by the ZGS passive filter, shown in Fig. 2. The results give the phase angle of each frequency component at the output of the rectifier.

Display Derived Ripple

The operator may push the DISPLAY DERIVED RIPPLE button to check the computation. In this mode, the computer uses the phases and amplitudes of the ripple components derived from the data to calculate V(t) at each value of θ_d. The graph is shown in Fig. 3 center. The amplitudes and phase angles of the components are given in the table at the bottom of Fig. 3.

A measure of the error is given by a number labelled FIT. This number is found by taking the difference between each measured ripple voltage and the voltage calculated from the phases and amplitudes of the ripple. This difference is divided by the measured voltage at each point and the ratio is squared. The number FIT is one minus the mean of this ratio.

Graph Phasor Set

The operator may see the results of the harmonic analysis by pushing a button labelled GRAPH PHASOR SET. This activates a subroutine that constructs the graphic display that is shown in Fig. 4.

The top lines on the right of Fig. 4 give the date and time of day for starting to take the set of data. The remaining lines on the right give the point in the ZGS cycle at which the data taking began. In this case it was 400.0 ms after the start of block 16 (flattop).

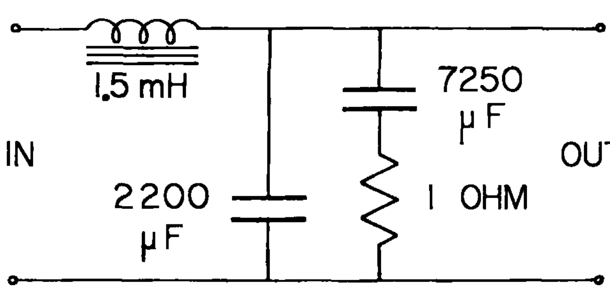
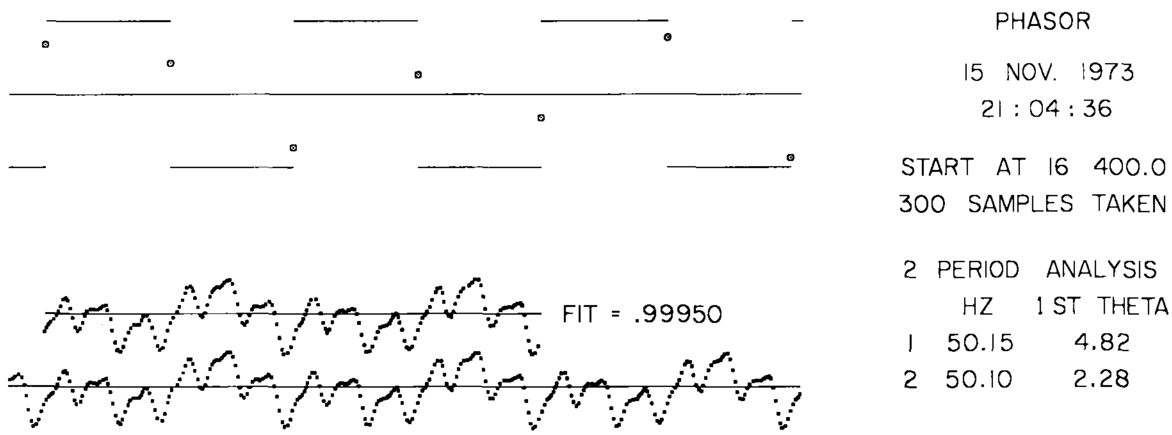


Fig. 2 ZGS Passive Filter



							RETAINED SET			
ALPHA	SET		AMP.	PHASE		AMP.	PHASE	ALPHA	SET	
0	0	0	- .2	0	dc	0	0	0	0	0
			1.1	29.3	1	0	0			
0	0	0	1.1	-111.7	2	0	0	0	0	0
			.2	-112.0	3	0	0			
0	0	0	.3	-130.1	4	0	0	0	0	0
			.1	-145.9	5	0	0			
0	0	0	1.4	- 76.6	6	0	0	0	0	0
			.1	- 82.1	7	0	0			
0			.0	138.0	8	0	0	0		
			.0	11.1	9	0	0			
			.0	47.8	10	0	0			
			.0	- 5.9	11	0	0			
			.6	15.6	12	0	0			

Fig 3. Display New Set and Derived Ripple

Three hundred data samples were taken and two periods were analyzed. The first period had a frequency of 50.15 Hz, while the second had 50.10 Hz. This difference is caused by the slowing down of the generator during the ZGS cycle. The angle θ_d for the first data point in each cycle was 4.82^o and 2.27^o.

The top graph gives the reconstructed ripple data that was calculated from the amplitudes and phases of the derived ripple components. The FIT number is also given. This graph is included in Fig. 4, as well as in Fig. 3, for identification purposes and because many people get a better "feel" for the data from an analog type display.

The upper bar graph of Fig. 4 plots the dc component and the amplitudes of the first 12 harmonics of the generator frequency. The vertical scale for this plot is shown above and to the left of the bar graph. The scale factor in volts per inch is changeable at will through the scope keyboard. These amplitudes are for the filtered voltage applied to the ring magnet.

The lower bar graph of Fig. 4 plots the phase angles x_r for the first 12 harmonics. The range of angles is fixed at +180^o to -180^o in accordance with the restriction on x_r in equation (8). These angles have been corrected for the phase shifts produced by the passive filter of Fig. 2. They are, therefore, the phase angles of the harmonic components at the output of the rectifiers. This is done to make it possible to determine which rectifier firing angles should be retarded or advanced to reduce the amplitudes of the ripple components.

The lower part of Fig. 4 lists several sets of numeric data. The column in the center lists dc and phases 1-12. The two columns to the left of center give the amplitudes in volts and the phase angles in degrees for the 12 phases and the amplitude of the dc component. These are the values used to calculate the derived ripple plotted at the top of Fig. 4.

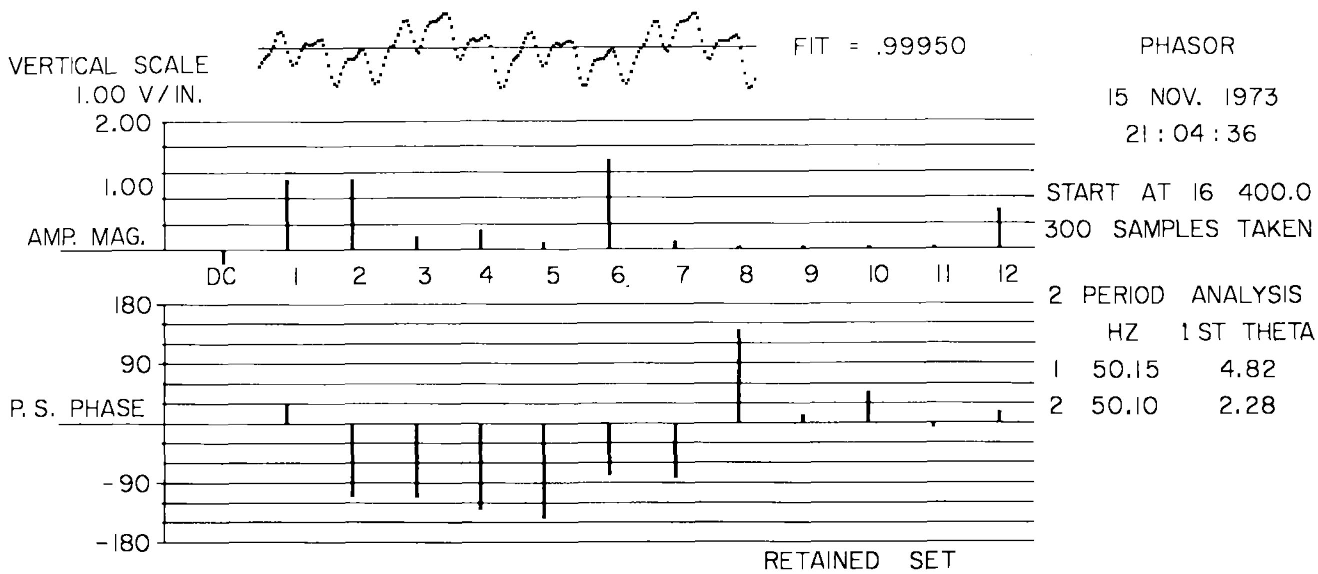
The table of numbers at the lower left records the alpha angle settings for the 12 phases and in addition, the full rectify setting. These are the settings of the ZGS control system that produced the ripple reconstructed at the top of Fig. 4. The numbers are in octal code and represent deviations from the ideal uniform spacing of rectifier firing angles. These numbers are recorded in the exact format in which they appear on the control panel of the digital firing angle control system.

These numbers are entered through the use of the ENTER/MODIFY ALPHA SET subroutine, and can be used by the operator when desired.

Retained Set

The operator may save a set of results, such as that presented in Fig. 4, by pushing the button labelled RETAIN THIS PHASOR SET. This activates a subroutine that stores the information in computer memory for comparison with future data.

The operator may then analyze a new set of data and call for GRAPH PHASOR SET. The result is the generation of a display such as shown in Fig. 5.



							RETAINED SET				
ALPHA SET			AMP.	PHASE		AMP.	PHASE	ALPHA SET		
77	36	77	-.2	0	dc	0	0	0	0	0
			1.1	29.3	1	0	0			
37	76	36	1.1	-111.7	2	0	0	0	0	0
			.2	-112.0	3	0	0			
76	36	77	.3	-130.1	4	0	0	0	0	0
			.1	-145.9	5	0	0			
36	74	36	1.4	- 76.6	6	0	0	0	0	0
			.1	- 82.1	7	0	0			
472			.0	138.0	8	0	0	0		
			.0	11.1	9	0	0			
			.0	47.8	10	0	0			
			.0	- 5.9	11	0	0			
			.6	15.6	12	0	0			

Fig. 4 Graph PHASOR Set

The numeric information at the top right of Fig. 5 is similar to that of Fig. 4 except it is for the new set of data. The derived ripple curve and the FIT number are also for the new set of data.

The bar graph for the amplitude now has two lines at each harmonic location. The left line in each pair gives the amplitude of that harmonic component in the new set of data, while the right line in each pair gives the amplitude of that harmonic component in the retained set. In this way, the amplitudes may be compared visually to determine the effect of the changes in the firing angles.

The bar graph for the phases also has a pair of lines at each harmonic location. The left line in each pair gives the phase angle for that harmonic component in the new set of data, while the right line gives the phase angle of that harmonic component in the retained set.

The numeric information, at the bottom of Fig. 5 on the right, gives the amplitude and phase angles for the retained set and in addition the alpha set that produced them. The numeric information, at the bottom on the left, gives the amplitude and phase angles for the new set of data and the corresponding alpha set.

Output

The program PHASOR is an interactive one so that most of the output is through visual observation of the computer driven scope display. Several options in the interaction can produce copies of the scope display on 8½" x 11" photographic paper. These include:

COPY NEW SET -- similar to Fig. 3,
COPY LEFT SHIFTED -- that portion of Fig. 3 that was analyzed,
COPY DERIVED -- derived ripple,
COPY PHASOR & ALPHA SET -- similar to Fig. 4, 5.

The "hard-copy" unit can produce a print in about ten seconds. No line printer output is provided.

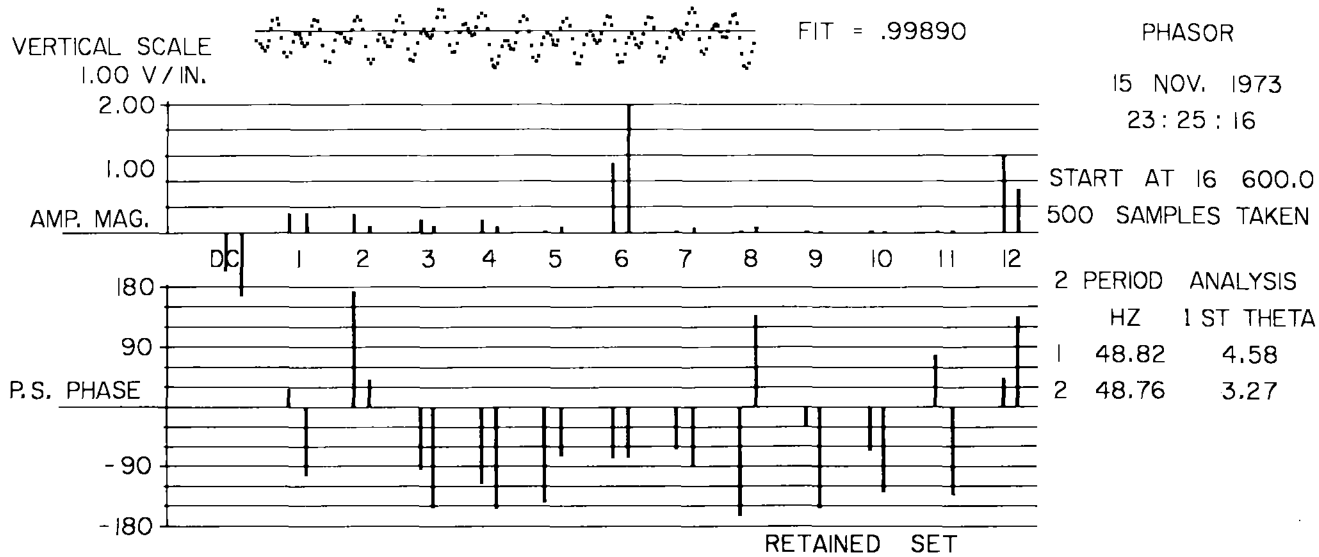
Calibration

The effects produced by changes in rectifier firing angle were experimentally investigated. For example, the firing angle of phase number 1 was advanced several electrical degrees to produce a large ripple on flattop. PHASOR was then used to measure the amplitude and phase of the harmonic components of the ripple thus produced. This procedure was repeated for several combinations of changes in firing angles of selected rectifiers.

The calibration data were useful in predicting which of the 12 rectifier groups should have their firing angles altered to reduce a given observed ripple.

Discussion

Analyses of ripple data were made for a variety of firing angle combinations during the calibration runs and for many actual operating conditions while ripple reduction adjustments were made. In all cases, the bar graphs similar to Figs. 4 and 5 showed very small or no amplitudes for the 5th, 7th, 8th, 9th, 10th, and 11th harmonics. The phase angles computed for these



							RETAINED SET				
ALPHA	SET		AMP.	PHASE		AMP.	PHASE	ALPHA	SET	
77	32	77	- .6	0	dc	-1.0	0	77	50	77
			.3	26.4	1	.3	-106.3			
32	76	32	.3	170.8	2	.1	43.1	46	76	47
			.2	- 96.2	3	.1	-153.2			
101	32	77	.2	-117.8	4	.1	-158.2	76	47	77
			.0	-146.0	5	.1	- 73.6			
32	76	32	1.1	- 78.3	6	2.0	- 77.1	46	74	46
			.0	- 63.7	7	.1	-90.2			
473			.0	-166.4	8	.1	138.3	470		
			.0	- 30.1	9	.0	-153.7			
			.0	- 68.0	10	.0	-131.3			
			.0	78.1	11	.0	-136.6			
			1.2	42.0	12	.7	136.0			

Fig. 5 Graph PHASOR Set With Retained Set for Comparison

harmonic components varied widely from one data set to the next which leads us to the conslusion that these harmonic components are largely the result of "noise" or inaccuracies in the input data.

We were not able to find a combination of rectifier firing angles that produced large or significant amounts of 5th, 7th, 8th, 9th, 10th, and 11th, harmonics. We therefore have amplitude and phase meaaurements at harmonic numbers 1, 2, 3, 4, 6, and 12 for a total of 12 measurements.

The control system has adjustments for each of the 12 phases but only 11 of these are independent variables as far as ripple is concerned. The 12th phase control and the "full rectify" control adjust the slope of the flattop. This slope is adjusted to zero before the ripple measurements are made.

Some thought was given to writing a program that would compute new firing angle settings from the ripple component amplitudes and phase angles. There appear to be enough measurements to permit the solving of a set of 12 equations. No adequate algorithm for this was developed in the very limited effort expended.

Inspection of the problem indicates that the ripple may be reduced one component at a time. This is the procedure used.

A perfect rectifier system will produce only the 12th harmonic, therefore this cannot be eliminated or effectively reduced by adjusting firing angles. On the other hand, the 6th harmonic can be increased or decreased in only one way. That is, all even numbered phases should be advanced an equal amount and all odd numbered phases retarded by the same amount. This method reduced the 6th harmonic amplitude to a minimum but would not make it vanish. The data indicate that the phase shift between our delta and wye connected transformers is only 28^{o} rather than the theoretical 30^{o}.

The first harmonic amplitude may be reduced by changing all of the 12 angles. In this case, the changes are distributed sinusoidally with the peak of the distribution determined by the phase angle of the 1st harmonic of the ripple. The 2nd harmonic may be reduced by a similar procedure except that the sinusoid for the distribution is the 2nd harmonic.

This program was used successfully to reduce the flattop ripple at the ZGS with the distributions for alpha angle changes determined manually. It is hoped that additional subroutines can soon be added to permit the computer to calculate the alpha settings that will minimize the ripple.