THE DESIGN, CONSTRUCTION AND APPLICATIONS OF AN ELECTRONIC A-C NETWORK ANALYZER

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ABSTRACT

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An A-C network analyzer is designed and built using chiefly standard low cost electronic parts.

General requirements of A-C network analyzers are presented and this information used as a foundation in choosing the required electronic components. The design of these components, namely a master oscillator, phase shifters, amplifiers, etc., is discussed in detail; especially where their characteristics and applications differ from what would normally be considered routine.

Several problems are solved with the aid of the analyzer and it is shown that it has a wide variety of possible applications.

Finally, the limitations in the design are discussed and several suggestions for improvement are given.

PREFACE

This thesis is the result of twelve months work undertaken by the author in the Department of Electrical Engineering, University of Manitoba, in designing and constructing an electronic a-c network analyzer. Most of the initial planning and design was carried out in the summer of 1958 with the remainder of the work being completed in the following summer.

In general, the aim of the research was to design and build an electronic analyzer, to a certain extent comparable in versatility with the commercially available types of today, using low cost standard radio parts.

Since by far the greatest portion of the time involved was spent on the design and construction of the various electronic components that go to make up the analyzer, the major portion of the paper is devoted to this aspect of the work. The second portion of the thesis relates some of the author's experiences with the completed analyzer. A brief outline of its possibilities and its shortcomings is also included.

I wish to sincerely thank Professor J. P. C. McMath for his encouragement and suggestions throughout the entire period. I also wish to extend my thanks to Mr. T. J. White and Mr. R. Woods for their timely advice and help during the period of construction.

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GENERAL CONSIDERATIONS OF THE PROBLEM

I. INTRODUCTION

Although the widespread use of a-c network analyzers has become prevalent only recently-just about every power utility has possession of, or at least, has access to one - they are by no means anything new. The forerunners of the modern analyzers, the d-c circuit boards, were known as far back as the early 1920's. The first a-c analyzer to receive widespread notice by those concerned was built at the Massachusettes Institute of Technology in 1929. This was a large and bulky apparatus.

The analyzers of today although they are still large and require at least one fair sized room for their installation are a great deal more flexible and accurate than their older counterparts. With these modern units it is possible to solve just about any power system circuit problem that one might come across and do so in relatively short order. There still remains, however, one detrimental factor which prohibits the universal use of the a-c analyzer by institutions of learning, the small electrical equipment manufacturer and even some of the smaller power utilities. This factor is cost. The purchase price of a good analyzer today is roughly one quarter of a million dollars and this sum of money is difficult to obtain for such purposes by most if not all universities and technical colleges for example. Thus, if the analyzer is to be used even more extensively and in a more diverse manner than it is today, the cost must be considerably lowered.

Herein is described an analyzer which even in a prototype was produced at relatively very low cost and yet showed promise of very satisfactory performance. Although no cost analysis of producing such equipment commercially was carried out, it may be assumed that the cost of a mass produced analyzer would be considerably lower.

It is agreed that there exist at present many different types of a-c network analyzers; some more costly than others and some existing only as prototypes at universities and technical colleges, etc. Hence, no claim is being made for complete originality as electronic type network analyzers have been built before.[1] It is believed, however, that the approach to the problem is unique. It might be mentioned here in passing that it is not the intention of this thesis to investigate all the various methods by which other types of a-c network analyzers have been designed; nor is it intended

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[1] See, for example, Ryder, J. D. and Boast, W. B.; "A New Design for the A-C Network Analyzer" AIEE Transactions, vol. 65 (1946), pp. 674-79.

to delve into all the possible uses to which an analyzer may be put. Whenever it seems necessary a little of both will be considered. However, if the reader requires a more thorough treatment he is requested to refer to the literature. Some excellent sources of this information are listed in the bibliography.

The thesis is divided into 5 parts. The first deals with the general requirements of an analyzer together with an account of the layout of what might essentially be called a block diagram of the system. The second part deals with each component part of the system (oscillator, amplifiers, etc.) and the third with the assembly of the components. In the fourth section an account is given of the solution of several problems on the analyzer. Although these may appear to be very simple, they do serve to illustrate the performance of and several applications of the analyzer. Included also is a brief discussion of other problems to which the analyzer may be conveniently applied. The fifth and final section contains material describing the limitations of the equipment and, in the author's opinion, what may be done to improve it.

II. THE COMPONENTS OF AN A-C NETWORK ANALYZER

Essentially, a large modern a-c network analyzer is composed of the following:

1. A number of sources of a-c voltage each of which may be varied continuously and independently in amplitude and phase relative to each other. These are generally known as "generator units".

2. A set of circuit elements. That is, an assembly of resistances, capacitances and inductances the magnitudes of which may be varied continuously or in small steps over a wide range. Frequently, in the modern analyzer some of these are assembled in groups of π's and T's and may be used directly to represent a power system transmission line. These are known as "line units". Other combinations, for example a resistance and an inductance in series, can be plugged in directly as power system loads and are known as "load units".

3. Metering facilities for the measurement of voltages, currents, watts and vars in any part of a circuit being studied.

4. Mutual coupling transformers (1:1 ratio) for purposes such as the representation of the mutual impedances of transmission lines in zero sequence networks.

5. Autotransformers.

6. An assembly of relays, plugs, jacks and other equipment necessary for interconnecting the above items and

to facilitate the rapid measurement of voltages, currents, etc.

In addition to containing the above mentioned units the network analyzer must be so arranged that it can be used for rapid calculations pertaining to any system regardless of the voltage or total power. This is made possible by the use of the "per-unit" system[2] for representing voltages, currents, power and other circuit parameters. With this in mind, every a-c network analyzer has its own per unit base voltage, base current, etc., the magnitudes of which are in the hands of the designer.

III. PRELIMINARY CONSIDERATIONS IN THE DESIGN OF THE SYSTEM

Introduction

There are several items of paramount importance which had to be kept in mind before any actual design work was even attempted. These will now be discussed.

Since funds for this sort of project were scarce, economy was a key word to be remembered throughout the entire design procedure. Arising out of this consideration then was the decision to build an analyzer with only three generator units, with provision being made for the eventual addition of

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[2]It is assumed that the reader is familiar with this method of representing power system parameters.

another nine when funds became available. Further, it should be possible to make any number of additions at any time without having to make any major changes to the chassis as a whole. The use of relays and other costly switching equipment to facilitate rapid metering, etc. was also out of the question. All of this would have to be done with relatively inexpensive plugs and jacks of various types. The number of accurate meters was also limited and after some deliberation it was decided that a good vacuum tube voltmeter would be purchased and used (with accompanying shunts) for the measurement of voltage and current. The measurement of real and reactive power proved to be a problem, however, as the frequency to be employed (1592 cps.) ruled out the possibility of using any of the instruments already available in the laboratories of the Electrical Engineering Department. Further, since the analyzer was to operate at a very low base power (10 watts) the wattmeter and/or varmeter would have to be of a type that draws negligible power from the circuit being measured. An instrument of this type can be very costly. Thus, a direct reading phase meter was decided upon. This would then enable the reading of phase angle between voltage and current from which the real and reactive power could be readily calculated. Furthermore, the phase meter could be used in other instances; as in the measurement of phase angles between two voltages or in the setting of the generators to their proper phase. The decision to use a phase meter was also a matter of expediency. A fairly accurate one was available in the laboratory and if time permitted a good one could be designed and constructed. If not, the existing meter could be used. In the light of neatness and order in use, it would be proper to build the measuring instruments right into the analyzer chassis. However, again out of the consideration of economy, the meters would have to be separate from the system so that they might be used elsewhere in the laboratory if so desired.

From a consideration of the efficiency of use of the analyzer circuit elements, arose the decision to leave the resistors, inductors and capacitors separate and not group them in "line units" or "load units". This decision was further backed by the fact that the analyzer would find considerable use in problems other than those involving power system studies and when this was the case, the circuit elements would not be needlessly tied up in groups which could not be utilized in that particular problem.

Choice of Base Quantities

The analyzer was to be built of common electronic components. This gave a very good idea of what the operating voltages and currents would be. Now in a system of this sort one naturally anticipates a great deal of inter-component wiring and hence the serious problems which might arise due to stray coupling (for example, power frequency hum pickup, crosstalk, etc.). Of course, this may be avoided by the use of extensive shielding of all wiring and components but in the end this is relatively expensive as well as time consuming. To avoid stray coupling problems it was decided to operate at a fairly high power level, low impedance and use a relatively low audio frequency. Thus the base quantities chosen are:

Base power = 10 watts

Base voltage = 100 volts

Frequency = 10,000 rads./sec. (1592 cps.)

From this choice we may easily obtain by calculation:

Base current = 100 milliamperes

Base impedance = 1000 ohms

Base inductance = 100 millihenries

Base capacitance = 0.10 microfarads

In conjunction with this, a consideration of the possible variations in voltage and current of a typical power system during faults, etc. as well as the fact that the analyzer would be used for problems other than those of power system type, it was decided that each generator should be capable of having its voltage and power output varied continuously from 0 to 2 pu. (per unit) and its current from 0 to 20 pu.[3]

The Basic Layout of the A-C Network Analyzer

Since the generator units would each have to put out a-c voltages of exactly the same frequency with adjustable relative phase it was obvious that all the generators must be synchronized in some manner. This was accomplished by the use of a master audio oscillator driving power amplifiers each of which represents a generator unit. From this point on, the basic layout is relatively simple and for the 3 generator system the a-c network analyzer is shown in Fig. 1. This constitutes a single line block diagram of the basic component parts of the analyzer. The next problem is the choice of the basic electronic circuitry that will go to make up each component.

Considerations Regarding the Analyzer Components

At this point a great deal of investigation consisting mainly of a survey of the existing literature on the various subjects was carried out in order to determine the following:

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[3] Such currents are encountered in most power systems under fault conditions.

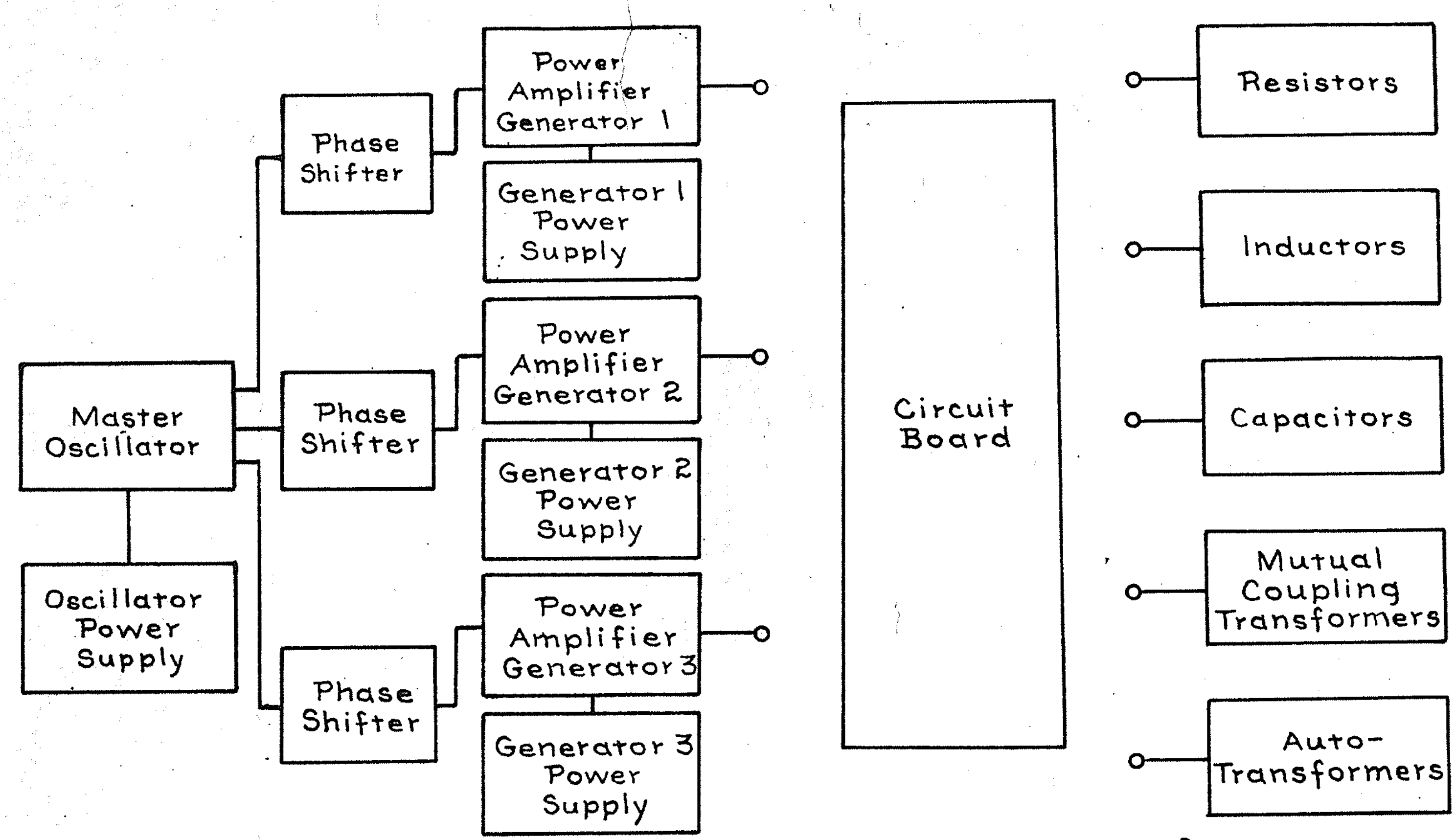

Figure 1. Block diagram of network analyzer. The final designs of the electronic components may be found on the following pages: master oscillator—18 and 27; oscillator power supply—31; phase shifter—51; power amplifier—63, 75 and 89; power amplifier power supply—91; and circuit board layout—99.

(a) Type of oscillator.

(b) Methods of phase and amplitude control for the generators.

(c) Type of preamplifier and power amplifier.

(d) Method of coupling these units.

Some of the subject material covered is listed in the bibliography. During this investigation the following criteria were kept in mind:

(a) The phase of each generator must be continuously adjustable from 0° to 360°.

(b) The amplitude must be continuously adjustable from 0 to 2 pu.

(c) The amplitude and phase controls of each generator should not interact.

(d) The total harmonic distortion in the output of each generator when delivering 1 pu. power (10 watts) should be less than 1%.

(e) The output of each generator should be stable in amplitude and phase at whatever value these are set.

The conclusions arrived at from the latter considerations will now be summarized.