SYSTEM STABILITY EVALUATION
USING THE MINIATURIZED A-C NETWORK ANALYZER

by
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I. INTRODUCTION

The fundamental relationship from which stability evaluations can be obtained have long been well established. The mathematical expressions from which stability is determined are relatively simple in themselves, even for complex networks involving several machines. However, the direct solution of the simultaneous equations involved cannot be easily accomplished as it becomes quite tedious and laborious. Although the method of symmetrical components, in the case of unbalanced faults, provides a more feasible solution, the amount of work and the possibility of making errors, especially when dealing with a multi-machine system, are sometimes discouraging. Different calculations for different system conditions is required and much time is spent for the reduction of the network. Present day techniques using machine methods, cuts the amount of work and time considerably and system conditions can be simulated and observed with direct measurements.

The earliest type of the network computing devices were mostly a miniature network of an existing power system. These are scaled down versions of the actual power system simulated, representing the most important features which are considered significant and indispensable. One of the earliest devices was a d.c. calculating board and was used for short circuit studies. Refined versions of this kind of analyzer
are in wide use today. Later, alternating current was employed, and led to the necessity of representing phase angle differences between synchronous machines for load flow and stability studies. These were 3-phase miniature systems, having the same frequency as the actual system with rotating machines of appreciable size, capacity and voltage. They were not well adapted, however, primarily because of their cost and their instability when a multi-machine system is represented. Also difficulty arises due to the fact that normal relationship of stability cannot be retained, as the model scale is quite reduced. 1)

By the introduction of the method of symmetrical components, 3-phase systems can be studied merely from a single phase analysis. Following this principle, single phase a.c. network analyzers were developed and analyzers were provided with variable circuit elements so that a study of different systems could be performed on the same analyzer. An example of this kind of analyzer is the M.I.T. Network Analyzer, employing static phase shifting transformers to represent generating stations, thereby eliminating the difficulties associated with rotating machines. 1) Higher frequencies were employed, thereby reducing the size of the analyzer elements. An advantage of using static phase shifting devices to represent generators is that static stability can be studied even beyond the steady state stability limit of the system.

Further improvement of the network analyzer, primarily to fulfil the possible amalgamation of the techniques and apparatus common to electronic and radio engineering led to the development of a complete
electronic instrument. 2) Investigations showed that the use of 10 KC frequency is advantageous. Improved performances of the network elements as compared to that of conventional equipments, and appreciable reduction in cost and size, result in the wide use of this kind of analyzer nowadays.

For handling problems which are too complicated to justify long-hand computation, but too small to justify time on large network analyzers, miniaturized network analyzers which are scaled down versions of the former are available at present. 3) It is the purpose of this research to investigate the applicability of the G.E. Miniaturized A.C. Network Analyzer for system studies, with special regard to stability problems.
II. THE INVESTIGATION

A. Power System Stability Studies on the Network Analyzer

Power system stability which may be defined as, that property of a power system which insures that it will remain in operating equilibrium through normal and abnormal conditions, is one of the most important phenomena encountered in power system operations. Under stable operation the angular position of the various machine-rotors, stay practically within a certain angle relative to each other. During transient disturbances, however, these rotors may swing apart and the system becomes unstable. The swing curve, which characterizes the angular position of a machine rotor with respect to time under transient conditions, is the most used data to determine whether or not the machine will remain in equilibrium with the system.

If all machines (in many cases only synchronous machines need be considered) in a system under a certain type of transient disturbance have the tendency to swing together, the system is considered stable for the particular condition.

An important criterion in the determination of the stability of a system is: A system is considered to be in stable operation when the system is stable during the first swing of the machines, following a transient condition, including those with the longest period. In most cases this is true, as the system will more likely be stable during subsequent swings if stability is maintained during the first swing.
Longhand calculation in evaluating the swing curves of the various machines is very laborious, especially when a detailed analysis is required. By the aid of a network analyzer, the time and work required is very much reduced. Network reduction, which is most time consuming will be unnecessary, as the actual system is exactly represented on it. Where reduction is necessary, because of the limited available network elements, equivalent networks can easily be obtained through measurements and a little computation. Also initial phase angles of the machines in the system can directly be obtained after the system conditions such as voltages and load flows are reproduced on the analyzer.

Direct methods for obtaining swing curves with the aid of a network analyzer and interconnected equipments have also been developed. Different possible schemes are proposed, some of the most frequently applied methods being used of a mechanical integrator directly coupled to the shaft of the analyzer generators, and the use of an analog computer. However, all the proposed schemes up to now are uneconomical, unless a large power system is considered.

The miniaturized network analyzer, developed to handle comparatively small power system problems, is obviously inadequate for such direct determinations. Also technical considerations prevent the possibility of miniaturized network analyzer use within any proposed scheme mentioned. This does not, however, become a serious objection, as swing curve evaluation can satisfactorily be obtained by the point by point method.
The General Electric Miniaturized
A.C. Network Analyzer
Before stability studies can be performed on the G.E. Minaturized A.C. Network Analyzer, it will be necessary first to calibrate the phase angle dials, as such is not provided on it. Actually phase angle meters specially built for the analyzer are available, but because of economical reasons was not purchased. For educational purposes, where strict accuracy is not of major concern, it will be sufficient to calibrate the phase angle dials directly, using several possible simple methods. Relative accuracy of the method of calibration should be considered, however and application to stability problems can be used to test the validity of such calibration for the use of the analyzer in stability studies.

B. Analysis of the G.E. Minaturized A.C. Network Analyzer

Basically the G.E. Minaturized Network Analyzer does not differ very much from the large analyzers. However, it has limitations in the scope of the problem which can be handled and the size of the system which can be represented. It technically differs in the type of instrumentation and the units it is composed of.

A brief description of the analyzer will be included in this section. For complete information The Minaturized Network Analyzer Instruction Book should be consulted. 3)

The functional blockdiagram of the analyzer is described in fig. 1. The diagram shows that the analyzer consists basically of one 10 kc oscillator, supplying signals to four generator units. Each generator unit consists of a phase and amplitude control unit and an
Fig. 1. Functional block diagram of the G.E. Miniaturized A.C. Network Analyzer.
amplifier in series. The magnitude of the voltage output can be adjusted with the voltage dials, and the phase angle with the phase angle dials. All of them are mounted on the right of the front panel of the analyzer. Voltage adjustment can be controlled by meter readings, but phase angle adjustment can originally not directly be controlled. This requires a phase angle meter or calibration of the phase angle dials. Phase angle control is provided in four 90 degree steps. In studies of power system operation, the voltage magnitude adjustment simulates adjustment of the excitation of the represented machine, while the phase angle adjustment simulates the adjustment of the governor of the prime mover.

Seventy-one elements, variable in magnitude, are available. Table I lists the various kinds of network elements. Adjustment of these elements is obtained by means of dials and switches on the front of each individual unit. All line and load units (except high impedance load units), may be set up as series or parallel LR circuits. The most convenient configuration of the load is a parallel LR circuit arrangement, since this allows independent adjustment of watt and var flow. The setting of the elements is obtained through watt and var measurements or voltage and current measurements.

All quantities on the network analyzer are given in per unit.

Contrary to the large network analyzers, the analyzer is not provided with line units and mutual transformer units. For the simulation of a circuit line 12 variable capacitor units, which can
Table I. Network Units of the Miniaturized Network Analyzer

<table>
<thead>
<tr>
<th>Unit</th>
<th>Number per Analyzer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator units</td>
<td>4</td>
</tr>
<tr>
<td>Buss units</td>
<td>15</td>
</tr>
<tr>
<td>Line units</td>
<td>30</td>
</tr>
<tr>
<td>Capacitor units</td>
<td>12</td>
</tr>
<tr>
<td>Auto transformer units</td>
<td>4</td>
</tr>
<tr>
<td>Load units</td>
<td>10</td>
</tr>
<tr>
<td>Reference units</td>
<td>1</td>
</tr>
</tbody>
</table>
be connected at both ends of a line unit are available. As the analyzer is primarily intended for solving medium and small size power system problems, therefore with relatively short transmission lines, in most cases the effect of capacitance on the line is disregarded. Also, neglecting zero sequence mutual impedance in this case does not show any appreciable effect. However, where mutual coupling has to be considered, an equivalent network can be set up. 9)

Of most importance is the metering instrument. This is a specially built dynamo-meter-type wattmeter, and can function either as a volt-, am-, watt-, or var-meter. The calibration of the scales are given in per unit. Using meter switches, the desired quantities can be measured on the meter. A directional switch will indicate the direction of the real and reactive power flow. Only scalar quantities can directly be measured and the meter leads can be plugged into any desired point on the network setup. Rectangular and polar form of voltage and current can be obtained indirectly, by measurements and calculations.

To keep coupling between circuits to a minimum, a low voltage of 10 volts is employed with a base impedance of 1000 ohms. The resulting base current is 10 ma.

At 10 kc the problem of capacitive coupling between circuits and shunt lead capacities can be severe, as complete shielding is impractical. The Miniaturized Network Analyzer, due to its compactness, has short interconnecting leads and therefore, shunt lead capacities are negligibly small.
Under the proposed method of calibrating phase angle dials, no strictly accurate result could be expected. However, stability determination can be accomplished with satisfactory results. For more accurate results, as may be required in commercial use of the analyzer, it is advisable that phase angle meters be employed.

In general, analysis of power system problems with the aid of the analyzer is quite time-saving. The speed in obtaining the necessary data also depends upon the correctness of system representation, as improper programming will certainly yield wrong results. Therefore a careful preparation of the problem to be studied is necessary, and by the aid of the network diagrams any error can easily be detected. Also a good understanding of the theory of the problem itself is required.

Another advantage of the Miniaturized Network Analyzer is that the analyzer elements are all set in a compact unit and all adjustment can be performed easily within the vicinity of the metering instrument, so that when occasion arises the analyzer may be conveniently operated by one operator.

C. The Calibration of Phase Angle Dials

Three simple methods of calibrating the phase angle dials of the analyzer are considered. Construction of a phase angle meter will definitely require amplifiers, as instrument burden on the network should be limited to a desirable minimum so as not to alter the represented network conditions. This certainly will increase the cost of such a meter considerably.
As the network analyzer under investigation will be primarily used for educational purposes, the accuracy in phase angle adjustment is not very stringent. As has been mentioned, for more accurate result such as solution of problems for commercial purposes, a phase angle meter will be required.

Although extreme accuracy is not required, relative accuracy of the methods of calibration should be considered, and the methods with better results should be followed.

To test the validity of the method followed, investigation is made by comparing the result obtained through conventional computation with that through the analyzer aid of a simple stability problem.

1. The Lissajous Figure Method

Referring to the block diagram of the analyzer circuitry and particularly the generator circuit diagram, it is apparent that by proper connection to a high frequency oscilloscope, the phase shift between the generator input and output voltages can be determined by means of the usual Lissajous figure method (fig. 2 a, b).

It was found that with the phase angle dial in its minimum counterclockwise position, a phase angle shift between the input and output voltages already exists. This phase angle shift differs from one generator to another. This can be easily understood from the fact that even without any external load to the generator, the phase shift and amplitude control unit and the amplifier behaves as a burden on the oscillator or power source. The circuitry of the generator is so
Fig. 2a. Lissajous figure of the generator input and output voltages with the phase angle dial set at minimum counterclockwise position.

Fig. 2b. Lissajous figure of the generator input and output voltages with the phase angle dial set at 90 degrees.
designed as to limit the no load current, which is comparable to the magnetizing current of a static phase shifting transformer and therefore limits the inherent angular phase shift.

For practical reasons, it was decided to consider the minimum counterclockwise position of the phase angle dial of generator one as reference zero angle, so that an infinite bus can be simulated by leaving the phase angle dial of that generator at this position.

When using the Lissajous figure method, this means that effort should be taken to eliminate this internal phase shift or the angle reading at each position should have subtracted this amount. This will introduce more errors and hence is undesirable. An example of this elimination is to place a variable condenser across the input terminals of the oscilloscope.

Reading error is more appreciable, first because the linearity of the oscilloscope figure is limited to a small area around the center of the screen, therefore preventing accurate reading and second the waveform though not quite obvious is nonsinusoidal (fig. 3).

Also sensitivity of reading has to be taken into account, because with small variation of the phase angle dial, hardly any change on the Lissajous figure is observed.

2. The Wave Displacement Method

By means of a high frequency oscilloscope, wave forms of generator voltages can be obtained easily. A phase shift of the voltage will
Fig. 3. Waveform of the generator output voltage.

Fig. 4. 90 degrees displacement between the output and input voltages of a generator.
merely shift the waveform on the screen horizontally to the left or to the right depending upon whether it is a phase increment or decrement (fig. 4). The internal phase shift between the generator input and output voltages can then be easily eliminated by shifting the horizontal position of the image on the screen.

In this experiment a Tektronix Oscilloscope was used.

The generator input voltage is plugged into the trigger input terminals of the oscilloscope, while the generator output voltage is applied to the vertical input terminals of the oscilloscope. To determine the phase shift of the generator introduced by adjustments of the phase angle dial, it is merely necessary to determine the shift of the intersection between the waveform image and the horizontal axis, when subsequently the input and output voltages of the generator are applied. This is because each horizontal division of the screen represents a certain angle. This method still has the disadvantage of presenting appreciable reading error, due to the small scale of the screen. It is better than the Lissajous figure method because, as has been mentioned, internal phase shift can directly be eliminated.

3. The Power Transfer Method

Depending upon the accuracy of the metering instrument of the analyzer, the power transfer between two generators can be used to determine the difference in phase angle between them.
As will be shown later, the power transfer between two synchronous machines, neglecting resistances, is determined by:

\[ P = \frac{E_1 E_2 \sin \delta}{X} \]

where:
- \( P \) = power exchange between the two machines.
- \( E_1 \) = internal voltage of machine no. 1.
- \( E_2 \) = internal voltage of machine no. 2.
- \( \delta \) = phase angle difference between \( E_1 \) and \( E_2 \) which is approximately equal to the angle between the machine rotors.
- \( X \) = reactance between \( E_1 \) and \( E_2 \), including the internal reactance of the machines.

If the magnitudes of \( E_1 \), \( E_2 \) and \( X \) are adjusted at a value of 1.0 p.u., it is obvious that the power transfer between the two machines is:

\[ P = \sin \delta \quad \text{(p.u.)} \]

Power reading in per unit is then equal to the sine of the angular phase difference between the two machine voltages.

It is clear that the accuracy of this method of calibration depends upon the accuracy of the metering instrument. However, reading can be obtained more conveniently because of the larger scale division as compared to the screen division of the oscilloscope. Therefore, reading error can be limited to a small value. It should also be
remembered, that the assumption of a pure reactance will introduce a certain error, which will be investigated. As another advantage of this method it can be mentioned that the meter is sensitive to small variations in the network.

In view of better measurements which can be achieved by this method of calibration, it was decided to apply this method in calibrating the phase angle dials.

4. Calibration

Because the power transfer method depends upon the correctness of the meter indication, metering check out and linearity test is necessary. The metering checkout procedure and the necessary requirements that must be fulfilled, is described in Ref. 3, pp. IV-3 - IV-10. The checkout results agree with the necessary requirements. The purpose of this checkout is to determine whether or not the metering instrument is "in phase".

The result of the meter linearity test is plotted in Fig. 5.

As the scale is calibrated in per unit quantities, the indication on the meter scale is independent of the actual values. Therefore, if the indication of the meter is plotted against actual values and the curve obtained is a straight line, the meter is in proper operation.

According to the instruction book, meter linearity test is accomplished, if a voltage linearity test gives satisfactory results.

In following the power transfer method for calibrating the phase angle dials, it was found that different pairs of generators result in different scales. This is a result of inherent differences and
non-linearities of the electronic devices, and has to be investigated further. The idea was to calibrate the three other generators against generator no. 1. It is expected that all calibration will agree with each other. In this manner, phase angle calibration was accomplished by setting the phase angle dial of generator no. 1 at its minimum counterclockwise position, the reference zero angle of all generators, and calibrate the rest of the generators against it. At a predetermined phase angle $\delta$, the sine of that angle was calculated and the phase angle dial of the generator being calibrated was shifted until the power reading indicated a power transfer in per unit equal to $\sin \delta$.

5. Error Introduced by the Assumption of a Pure Reactance Impedance

As pure reactance can never be obtained, a small error due to the existence of resistance is introduced in the calibration of the phase angle dials. This error will be more appreciable, when the impedance is heated due to the flow of current. The error introduced by this phenomena will be investigated. It is necessary first to derive the equation of power transfer between two synchronous machines, taking into account the actual impedance between the two.

Consider a simple two-machine system consisting of one generator supplying its power to a motor. The internal voltage of the generator is $E_1$, the internal voltage of the motor is $E_2$, while the total impedance between the two internal voltages, consisting the impedances of both machines and the line, is $Z$. 
The following equations will then be obtained:

\[ E_1 = E_2 + iz \]

\[ I = \frac{E_1 - E_2}{Z} \]

\[ P = \text{Re} (E_1 I) \]

\[ = \text{Re} \left( \frac{E_1 (E_1 - E_2)}{Z} \right) \]

If we let \( E_2 = E_2 \angle \phi \)

\[ E_1 = E_1 \angle \delta \]

\[ Z = Z \angle \theta \]

then

\[ \rho = E_1 \angle \delta \]

\[ P = \text{Re} \left( E_1 \angle \delta \frac{E_1 \angle \delta - E_2 \angle \phi}{Z \angle \theta} \right) \]

\[ = \text{Re} \left( \frac{E_1^2 \angle \theta - E_1 E_2 \angle \theta - \delta}{Z} \right) \]

\[ P = \frac{E_1^2 \cos \theta - E_1 E_2 \cos (-\theta - \delta)}{Z} \]

1)

If resistance is negligible, \( \phi = 90^\circ \) and \( Z = X \), and obviously the power transfer is:

\[ P = \frac{E_1 E_2}{X} \sin \delta \]

2)

This was the assumption made in calibrating the phase angle dials. It is clear that the validity of this assumption depends upon how much \( Z \) deviates from its equality to \( X \).
<table>
<thead>
<tr>
<th>$P$ (p.u.)</th>
<th>$\delta$ (degrees)</th>
<th>Actual (degrees)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>0.037</td>
<td>5</td>
<td>5</td>
<td>0.000</td>
</tr>
<tr>
<td>0.173</td>
<td>10</td>
<td>10</td>
<td>0.000</td>
</tr>
<tr>
<td>0.259</td>
<td>15</td>
<td>15</td>
<td>0.000</td>
</tr>
<tr>
<td>0.342</td>
<td>20</td>
<td>20</td>
<td>0.000</td>
</tr>
<tr>
<td>0.423</td>
<td>25</td>
<td>25</td>
<td>0.000</td>
</tr>
<tr>
<td>0.500</td>
<td>30</td>
<td>29.97</td>
<td>0.100</td>
</tr>
<tr>
<td>0.574</td>
<td>35</td>
<td>34.98</td>
<td>0.057</td>
</tr>
<tr>
<td>0.643</td>
<td>40</td>
<td>39.95</td>
<td>0.125</td>
</tr>
<tr>
<td>0.707</td>
<td>45</td>
<td>44.88</td>
<td>0.267</td>
</tr>
<tr>
<td>0.766</td>
<td>50</td>
<td>49.85</td>
<td>0.300</td>
</tr>
<tr>
<td>0.811</td>
<td>55</td>
<td>54.80</td>
<td>0.364</td>
</tr>
<tr>
<td>0.866</td>
<td>60</td>
<td>59.77</td>
<td>0.384</td>
</tr>
<tr>
<td>0.906</td>
<td>65</td>
<td>64.60</td>
<td>0.620</td>
</tr>
<tr>
<td>0.940</td>
<td>70</td>
<td>69.54</td>
<td>0.661</td>
</tr>
<tr>
<td>0.966</td>
<td>75</td>
<td>74.26</td>
<td>0.997</td>
</tr>
<tr>
<td>0.985</td>
<td>80</td>
<td>78.82</td>
<td>1.500</td>
</tr>
<tr>
<td>0.996</td>
<td>85</td>
<td>82.60</td>
<td>2.900</td>
</tr>
<tr>
<td>1.000</td>
<td>90</td>
<td>84.65</td>
<td>6.320</td>
</tr>
</tbody>
</table>
Measurements show that for a reactor set at 1.0 per unit the components values are $X = 0.9993$ per unit and $R = 0.005$ per unit for which $\theta = 89.7^\circ$. Substituting these values into eq. 1) and remembering that $E_1$ and $E_2$ are set at 1.0 per unit we obtain:

$$P = 0.005 - \cos (89.7^\circ + \delta)$$
$$= 0.005 + \cos (90.3^\circ - \delta)$$

Table II shows the discrepancies in phase angle with the actual values.

As can be seen, the largest discrepancy is at $90^\circ$, where the error is 6.32%. This, however, can be avoided by varying the phase angle dial until the power transfer is maximum. At this point the phase angle difference between the two generator voltages, as can be seen from eq. 3), is equal to $90.3^\circ$. If this is followed the error introduced is only 0.33%.

6. Further Investigations

Two questions arise following the calibration of the phase angle dials:

1. Why do different combinations of two generators perform different calibration?

2. Will the calibrated scales hold true for every quadrant?

Before any attempt is made to answer these questions, several important generator characteristics will be investigated.
a. Internal Phase Shift

The internal phase shift introduced between the input and output voltages of a generator, differs from one to the other.

The wave displacement method is used to determine these phase shift and the following result is obtained:

- Generator no. 1 = 193.0°
- Generator no. 2 = 194.4°
- Generator no. 3 = 194.4°
- Generator no. 4 = 195.6°

This is the internal phase shift with all quadrant selector switch at the first quadrant position and with the phase angle dial at its minimum counterclockwise position.

The main source of differences in internal phase shift is in the amplifier for which no possible adjustment can be made. The internal phase shift introduced by the phase shifter alone is the same for each generator and is equal to 124.4°.

However, the differences in internal phase shift is not quite appreciable, therefore is not sufficient to answer the first question.

b. Output Voltage versus Load Current Characteristic

The load characteristic of generator no. 2 is plotted in fig. 6. Three kinds of loads are used, i.e. 1.0 p.f., 0.8 p.f. lead and 0.8 p.f. lag. The characteristic shows that as a result of the feedback employed in the generator, the voltage regulation is kept to very low values.
c. Output Voltage versus Phase Angle Characteristic

Fig. 7 shows the relation between the output voltage of generator no. 2 versus the phase angle according to the calibrated scale. The characteristic for 0.3 lagging and 0.3 leading p.f. loads coincide with each other.

d. No-load Output Voltage versus Phase Angle Characteristic

The no-load output voltage as a function of phase angle for the four generators is plotted in fig. 8. It shows that each generator performs appreciable different characteristics. This phenomena gives a stronger reasoning for the condition described in the first question.

The graph must be interpreted as follows:

For a given voltage, the phase angle as indicated on the calibrated scales differ from one generator to another. Hence, for a given voltage there exists a difference in phase angle, which varies between each pair of generators. These inherent phase differences, which are caused by the nonlinearity of the equipments, are not constant. It is selfevident that these differences will continue to exist when the generators are loaded. In calibrating the phase angle dials the voltages of each pair of generators were held at 1.0 p.u., the phase angle of one generator was held at its minimum counterclockwise position, while the phase angle dial of the other generator was shifted and calibrated according to the power transfer reading. Accordingly the mentioned phase differences are taken into account and are included in the total phase shift between the two generators.
Fig. 7. Typical Output voltage versus Phase angle characteristics at various constant loads.
Fig. 8  Output voltage versus phase angle characteristics at no load.
Since the inherent phase differences are not the same, it is now obvious that different combinations of two generators will result in different calibration. This answers the first question.

e. Actual Phase Shift Introduced by Phase Quadrant Selector

As has been mentioned, angle reading is provided in 90° steps. Measurements show the following phase shift introduced by the phase quadrant selector:

<table>
<thead>
<tr>
<th>Generator no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase quadrant selector position:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st quadrant</td>
<td>0.0°</td>
<td>0.0°</td>
<td>0.0°</td>
<td>0.0°</td>
</tr>
<tr>
<td>2nd quadrant</td>
<td>35.4°</td>
<td>89.9°</td>
<td>86.4°</td>
<td>86.2°</td>
</tr>
<tr>
<td>3rd quadrant</td>
<td>180.0°</td>
<td>180.0°</td>
<td>180.0°</td>
<td>180.0°</td>
</tr>
<tr>
<td>4th quadrant</td>
<td>274.6°</td>
<td>270.1°</td>
<td>271.6°</td>
<td>273.8°</td>
</tr>
</tbody>
</table>

The data shows that the angular steps are not exactly 90°. In stability studies this means that for regions where \( \frac{dP}{d\delta} \) is small, the obtained calibration will not show any appreciable error, since negligible power difference is introduced. However, if \( \frac{dP}{d\delta} \) is large, the deviation can be sufficiently large and may lead into incorrect results.
III. EXPERIMENTS

To test the validity of the calibration established, two simple stability problems will be solved by the aid of the analyzer. The theory which is behind the solution of these problems will be briefly outlined in the next chapter.

Problem no. 1: A 25 Mva 60 cycle water-wheel generator delivers 20 Mw over a double-circuit transmission line to a large metropolitan system which may be regarded as an infinite bus. The generator unit, including the water wheel, has a kinetic energy of 2.76 Mj. per Mva at normal speed. The transmission circuit has negligible resistances, and each line has a reactance of 0.20 p.u. at 25 Mva base. The voltage behind transient reactance of the generator is 1.03 p.u., and the voltage of the metropolitan system is 1.00 p.u. As a result of normal switching operation, one of the two parallel lines is opened. Compute and plot the swing curve.

Solution: The problem was solved both by conventional computation and with analyzer assistance. The obtained results are plotted on fig. 9 and a direct comparison between the two results can be analyzed. The point-by-point method is followed and a time increment of $\Delta t = 0.05$ sec is used. The period of oscillation of the analyzer evaluated swing curve is shorter by 0.005 sec or 0.9% from that of the conventionally calculated curve. The biggest difference in phase angle after 1 1/2
cycle of oscillation is about 1° or 3.5%. These discrepancies are a result of inaccuracy in reading of the phase angle, because the scale is calibrated with 5° steps. The deviations are within tolerable limits and both swing curves tend to have an increasing amplitude.

We can conclude, that as long as careful reading of the phase angles is performed, satisfactory results will be obtained. The analyzer is then applicable for evaluations of swing curves.

Problem no. 2: The second problem involves a three-machine system with interconnecting tie-lines between them and loads emerging from the buses. This problem is adapted from Ref. 6, pp. 89-109 so that direct comparison with the calculated result can be made. The system outline is given in fig. 10 together with the necessary data, all on a 100 Mva base. Line and generator resistances are neglected. A three phase short circuit occurs at point X, and it is desired to determine the stability of the system, when clearing of the fault is done in 0.40 sec.

Solution: The analyzer evaluated as well as the calculated swing curves are plotted on fig. 11. The calculated result shows that the system for that particular clearing time is unstable, whereas the analyzer evaluated swing curve shows that the system is stable. The swing curve of Wieboldt and Murphy stations, both analyzer evaluated and calculated, agree with each other. But the calculated swing curve of Lunt station shows that the machine phase angle increases indefinitely,
Fig. 10. Three machine system of Problem no. 2. All quantities are given in per unit on 100 Mva base.
while the analyzer evaluated swing curve shows that it swings back

tending to restore stability of the system.

**Discussion:** The calculated solution was obtained by neglecting
the resistances and capacitances of the system, so that only pure
reactances are involved. This, however, cannot be represented on the
analyzer, since a pure reactance can never be developed and capacitance
though quite small is always present within the analyzer network.
These factors tend to stabilize the represented system.

There is also another possibility that error is introduced by
assuming that the phase angle scale is valid for every quadrant. The
phase angles of Wiesboldt and Murphy stations extend up to the third
quadrant, therefore the phase quadrant selector switching introduce
two errors, one at each switching. However, as phase angle increment
is comparatively small for these generators, the influence of angle error
to the end result is not appreciable. The phase angle of the Lunt
generator on the other hand extends up to the fourth quadrant, introdu-
ducing four errors due to phase quadrant selector switching. As phase
increment for this generator is relatively large, this phenomena
introduces more errors.

To get better results, two points may then be taken into account:

1. If the phase angle increment is large, at each time of switching
the phase quadrant selector, a correction angle should be
introduced the value of which can be obtained from the list
in section 5e of this chapter.
2. Better results may be obtained if resistance is included. In this case the result will be much more in accordance with the actual system. The calculated solution obtained by neglecting the resistance is a pessimistic solution and is aimed to simplify the calculations. This is not necessary when using the analyzer.

The results show that with the calibrated phase angle scales, the analyzer can be adequately used for stability studies, and where necessary corrections can be applied.
IV. COMPARISON BETWEEN NETWORK ANALYZER AND CONVENTIONALLY CALCULATED STABILITY EVALUATIONS

The conventional solution of power system stability is usually obtained through simplifications. The result is therefore pessimistic. In other words, the result may indicate that a system under a particular type of disturbance and clearing is unstable, whereas because of the restoring effects which have been neglected in the computation, the actual system is stable. However, if the computed result indicates stability it is evident that the actual system is stable. Therefore a safety factor, which is a necessity in any engineering design, is introduced by neglecting those effects of secondary importance. Besides simplifications are necessary; otherwise computation becomes quite extensive and the results obtained through such accurate computation may not justify the time consumed. Network analyzer evaluations on the other hand can be obtained through a more detailed analysis, therefore a less pessimistic result is achieved. Also, a complete simplification, as can be made in computational methods, cannot correctly be simulated on the analyzer. This obviously is no objection since the simplifications introduce a wide range of safety factors.

The principal differences involved between the actual conditions and the conditions considered during stability evaluations should therefore be thoroughly understood.
Under normal operations, the mechanical input to a synchronous machine (corrected for rotational losses) equals the electrical output (corrected for electrical losses). Therefore under normal operations the rotor rotates at a constant speed. Each point on the rotor remains constant with respect to a synchronously rotating axis.

Under disturbances, however, the power input may be different than the power output and according to the law of conservation of energy a resulting accelerating torque will be experienced by the rotor.

The differential equation governing the motion of a generator rotor, called the swing equation, can then be written as follows:

\[
M \frac{d^2 \delta}{dt^2} + P_{\text{electrical}} + P_{\text{electrical}} + P_{\text{mechanical}} = P_{\text{mechanical}}
\]

\[
M \frac{d^2 \delta}{dt^2} = (P_{\text{mechanical}} - P_{\text{mechanical}}) - (P_{\text{electrical}} + P_{\text{electrical}})
\]

and may further be simplified to:

\[
M \frac{d^2 \delta}{dt^2} = \Delta P_a
\]

where:  
\( \delta \) = displacement angle of the rotor with respect to a reference axis rotating at normal speed.  
\( M \) = inertia constant of the machine.  
\( \Delta P_a \) = accelerating or decelerating power.  
\( \Delta = \) difference between mechanical input and electrical output after each has been corrected for losses.  
\( t \) = time.
The solution of this equation gives $\delta$ as a function of $t$ and a graph of such a solution is known as the swing curve. Since this equation involves many variables, an analytical solution will obviously be unfeasible. The point-by-point solution is the most feasible and widely used method. This solution is obtained by assuming that the accelerating power changes in steps with intervals $\Delta t$. Furthermore, as has been mentioned, other simplifying assumptions are required.

The common assumptions made in stability studies are:

1. Each synchronous machine is represented by a constant emf., the voltage behind transient reactance and a constant reactance, the direct axis transient reactance.

2. The mechanical angle of each machine rotor coincides with the electrical phase of the voltage behind transient reactance.

3. The input remains constant during the entire period of a swing curve.

4. Damping power and subsequent effects are neglected, (amortisseur effect).

5. The system network impedances remains constant corresponding to the normal operating frequency. Resistances are neglected.

Before analyzing the above mentioned assumptions, it is necessary to point out that in the fundamental analysis of machine operation the consideration of torques rather than powers is essential. In practical problems however, the actual deviation from synchronous speed is quite small, even during transient disturbances involving large
angular displacements. Therefore, powers instead of torques may be used with but insignificant error in most cases. Therefore, the analysis of transient stability will be primarily in terms of power.

The vector diagram of non-salient-pole as well as of salient-pole machine is shown in figures 12 a and b. 8)

The electrical power output of each machine during transient conditions can directly be evaluated from the vector diagrams are as follows:

- salient-pole machine:

\[ P = \frac{E_d E_t}{X_d} \sin \delta + \frac{E_t^2 (X_d' - X_q)}{2X_d X_q} \sin \delta \]  

\[ P = \frac{E_d E_t}{X_d} \sin \delta \]  

\[ P = \frac{E_d E_t}{X_d} \sin \delta \]

- non-salient-pole machine:

\[ P = \frac{E_d E_t}{X_d} \sin \delta + \frac{E_t^2 (X_d' - X_d)}{2X_d' X_d} \sin 2 \delta \]

\[ P = \frac{E_d E_t}{X_d} \sin \delta \]

Equation one and four are usually avoided in conventional computations, since they involve second harmonics. Because of its
Fig. 12a. Vector diagram of salient-pole machine. Resistance neglected; subtransient quantities are not shown.

Fig. 12b. Vector diagram of non-salient-pole machine. Resistance neglected; subtransient quantities are not shown.
simplicity equation three and four, which are similar to each other, are usually applied to determine the output power. Equation two is sometimes also used when the effect of saliency is to be considered. As a rule the power output will be adjusted for each step in the point-by-point calculations by which transient stability is determined.

Since the flux linkages with an inductive circuit cannot change suddenly, the voltage $E_d$ must have the same value directly after a disturbance takes place as it had before. It is then obvious that the assumption that the voltage behind transient reactance $E_i$ remains constant is incorrect. This will be clearly understood by careful study of the vector diagram. An investigation of equations three and four indicates that the angle involved in these does not represent the actual position of the field structure. The angle with respect to the field structure will always be larger than that used in computations. However, it is obvious that if stability is indicated in terms of the latter, that is, if the angle $\delta_i$ will finally approach the steady state, the angle $\delta$ must do the same thing. A typical power angle curve for constant $E_d$ versus $\delta$ and another for constant $E_i$ versus $\delta_i$ of a synchronous machine connected to an infinite bus through an external reactance is shown in fig. 13. From this figure it can be concluded, that as far as stability is concerned the assumption that the voltage behind transient reactance remains constant and that the mechanical angle of a machine rotor coincides with the electrical phase of this voltage will give results with sufficient reliability.
Angular position

Fig. 18 Typical Power Angle curve for a synchronous machine connected to an infinite bus through external reactance.
Since both conventional and analyzer method of stability evaluation are usually based on this assumption it is readily understood that it will always present a certain safety factor to the final result.

The assumption that the input power remains constant is derived from the fact that during the first instants after the occurrence of a fault, the governor of the prime mover would hardly make any adjustment. The governor will not act until the speed change exceeds a certain amount. However, in the consideration of subsequent swings, the effect of governors to assist in reducing sustained oscillations may be important. Thus, the exclusion of governor regulation during stability evaluations introduces another safety margin to the end result.

The analytical approach of damping and its subsequent effect on stability is not simple. Therefore, no attempt will be made to analyze it in detail, since it is beyond the scope of this analysis.

Almost all synchronous motors, synchronous condensers and synchronous converters and many salient-pole generators are equipped with damper or amortisseur windings. There are several reasons for providing a synchronous machine with damper windings, some of which are directly related to stability. These are damping oscillations during transient disturbances such as fault, sudden change of load and switching, and providing a braking torque on a generator during unsymmetrical faults.
The existence of damping power means a reduction in the net mechanical power input, therefore, reducing the accelerating power $P_a$. Evidently, during transient disturbances the damper windings have the tendency to keep the machine in synchronism. In most cases high resistance amortisseur windings have proven beneficial for stability.

It is clear now, that by neglecting the damping power and its subsequent effect another safety factor is introduced. The simplified computation either by conventional methods or analyzer aid can be carried on satisfactorily.

The presence of resistance in the actual network provides another form of braking power. Additional losses which are dissipated in the resistances has to be supplied from the mechanical power input. This will be clear if we look back to equation one, Chapter II, C section, which is the equation of the generator output in a two-machine system. The second term on the right hand side is the electrical power output, whereas the first term on the right hand side of the equation is the power dissipation which has to be supplied by the generator. The total power output is therefore larger than in the case where resistance is neglected. This additional power output results in a decrease in the accelerating power and hence tends to restore stability. For the motor on the other hand, inclusion of resistance means that during disturbances the electrical input decreases hence a sacrifice in stability. For the generator, neglecting the effect of resistance provides a safety margin to the end result, whereas for the motor the
opposite is true. For the latter the total safety margin, however, remains large, hence does not appreciably affect stability evaluations.

From the preceding discussion it is obvious that the simplified assumptions as a whole introduce a wide range of safety factors. The only assumption which cannot completely be simulated on the network analyzer is the exclusion of resistance. Since no matter how small, resistance is always present in a reactor, stability evaluations on the network analyzer are therefore much in accordance with the actual system condition. This also means, if the conventionally calculated result is not in accordance with the analyzer evaluated result, that it is not necessary to conclude that the latter is wrong. Since safety margin is large, a certain amount of resistance which will be included during network analyzer evaluations of stability is tolerable, merely reducing the safety factor.

We can then finally conclude that in general the stability evaluations using the analyzer under investigation will yield satisfactory results, and because of inclusion of some resistance, offers greater accuracy.
V. CONCLUSION

The phase angle dials of the Miniatized Network Analyzer have been calibrated by means of the power transfer method. The investigation shows that based on the calibrated phase angle dials, the analyzer can be used for power system stability evaluations with fairly accurate results. Conventional stability evaluations are usually made through simplifying assumptions and the exclusion of many effects beneficial to stability, resulting in a wide range of safety factors. When the network analyzer method is followed, one of these effects which is caused by the presence of some resistance in the analyzer network cannot be disregarded. The presence of some resistance tends to offer the analyzer calculated result greater accuracy. During stability evaluations it may be advisable to introduce a correction in phase angle readings on changing from one quadrant to another. This is due to the fact that the phase shift introduced by each step of the quadrant selector is not exactly equal to 90 degrees.

From the experiments it can be concluded that as long as careful reading of the phase angle dials is observed, in general, stability evaluations on the investigated network analyzer will yield satisfactory results.
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ABSTRACT

One of the most important problems involved in power system operations is stability evaluations to determine whether or not a system will remain in synchronism during transient disturbances. The mathematical expressions from which stability is determined are relatively simple in themselves; however, the direct solution of the simultaneous equations involved cannot easily be accomplished by conventional methods. Present day techniques, using network analyzers, cut the amount of work and time considerably. For handling problems which are too complicated for conventional computation but too small to justify time on the large network analyzer, miniaturized network analyzers are available. One of such analyzers is the G.E. Miniaturized A.C. Network Analyzer, which is the object of this investigation.

The investigation shows that it is possible to calibrate the phase angle dials and use them in conjunction with stability evaluations. The results so obtained are fairly accurate and where necessary, corrections can be employed.