SERIES-CAPACITOR COMPENSATION FOR SYNCHRONOUS-CONDENSER REACTANCE

by

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A THESIS

submitted to

OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1951

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General Historical Introduction

Experience serves many times as a guide where knowledge of fact is dubious and untried. This applies to the many ramifications of life, as well as science and engineering. Because our short time in life cannot suffice to provide all the answers, man has developed a wisdom and an understanding precocious for his years by studying the past history and experience of his forefathers. By this method we hope to profit from past mistakes, good and bad judgement, and previous accomplishments. It is with this idea in mind that the subject of synchronous condensers is introduced.

The story of the synchronous generator-motor commenced about 1821 when the English Chemist-Physicist, Michael Faraday, working with Sir Humphrey Davy in London, produced for the first time the rotation of wire carrying current in a magnetic field. Notable scientific contributions during that period from Ampere, Biot, Savart, and Oersted rapidly expanded man's knowledge in the field of electro-magnetics. In this country Professor Joseph Henry, teacher of Physics at Albany Academy, constructed the first electro-magnetic motor with a crude type of commutation in 1829. By 1837 Thomas Davenport had developed D.C. motors for industrial use. Continual progress during the next forty years led to the further improvements of slotted armatures, electro-magnetic field excitation as a replacement for permanent magnets, and laminated cores to reduce eddy-current losses. Invention and improvements could, however, scarcely remain in stride with the demands of industry. In 1857 the first electric locomotive made its historical trip on the Baltimore and Ohio Railroad. Electric street-lighting came into existence in Paris in 1878 and in New York in 1880. The California Electric Company became the first enterprise to sell electric service in 1879.

About 1878 it was demonstrated that alternating-currents would provide better results on illumination circuits than conventional direct-current of that day. In 1880 Ganz and Company pioneered the development of the alternating-current system in Europe. Our own country received its first alternating-current service in 1886 when the Westinghouse Company operated an experimental lighting system in Great Barrington and later in the same year installed an A.C. lighting system for Buffalo, New York. However, A.C. remained strictly in the field of illumination for the first years, and even there Westinghouse experienced virulent attacks from the Edison Company and proponents of the already established D.C. systems. Advocates of D.C. claimed alternating-currents were unsafe, and as testimony they pointed to the use of A.C. for the electrocution of criminals. Nonetheless, they found it difficult to equal the installation bids of the A.C. people, and their accusations little daunted the progress of the Westinghouse Company. Eventually the storm abetted. The General Electric Company absorbed the Edison Company in 1892 and began A.C. achievements for themselves.

Toward the latter part of the nineteenth century engineers began to appreciate certain unique advantages of the A.C. system. Furthermore, the commutator on D.C. machines imposed limitation upon size and complicated their design. With no such restrictions upon A.C. machines, the electric industry soon began to exploit the new field once George Westinghouse had displayed the merits of such a system.

Initially the obstacles to A.C. machinery expansion were great. A fundamental bottle-neck existed in the pulsating character of the A.C. current wave, which would cause the early motors to stop on dead center, or at the zero of the current wave. In 1888 Tesla surmounted this difficulty with the discovery of the two-phase system and the rotating field principle.

Westinghouse bought Tesla's patents and utilized them to produce the first induction motors, the first A.C. motors that could compare favorably with the well established D.C. motors. As the alternating-current motor came into prominence the need for a standard frequency became increasingly important. Finally in 1892 the Westinghouse Company decided upon 60 cycles, a much lower frequency than those previously used. Also, the same company supported the two-phase system during this transition period from D.C. to A.C., because less adjustment was required on the existing distribution circuits. The existing D.C. distribution circuits represented a considerable outlay of capital. It is apparent, therefore, why the new alternating-currents evoked heated controversy and why the transition from D.C. to A.C. was gradual. However, the Westinghouse engineers ameliorated the situation somewhat with the introduction of commercial rotary converters about 1892. Then A.C. transmission could be employed to supply power to users of both A.C. and D.C.

Original development of alternating-current systems depended in no small measure upon the transformer, for without it alternating-current possessed none of the advantages of high voltage transmission and lost the inherent flexibility of a system with transformation.

The transformer evolved through many stages from the early experiments on the induction coil by Joseph Henry to the modern oil-filled transformer as we know it today. Early investigators in the '50's and '60's, such as Ruhmkorff, Poggendorff, and Leon Foucault, exposed most of the principles of the induction coil with which they produced high voltages by interrupting the D.C. current in the primary winding. These principles were adopted to good advantage when men began to search for the most effectual means of electric power transmission. J.D. Gibbs and L. Gaulard of Paris displayed the first A.C. transmission system with transformation in 1883 at the Westminister Aquarium in London. George Westinghouse was so impressed he purchased American patents on the new A.C. device in 1885. Under his competent promotion Westinghouse Company developed the first commercial transformers in this country, and as we have seen, initiated the first A.C. systems in this country. By 1887 Westinghouse already had patents for the use of nonconducting, moisture-excluding fluids or gases, and so attained the basic design of the oil-filled or air-cooled types familiar to us today.

At the close of the nineteenth century the basic elements comprised in the modern electric power systems were already invented, applied, and firmly rooted in fields of the electric industry. Direct-current motors and generators maintained a good volume of business in the fields of illumination, railway, and metal processing. Their sources of energy were, however, yielding ground to the A.C. generators or the synchronous alternator. Arrival of the transformer and induction motor supplied added impetus to the alternating-current movement and soon proved the intrinsic economy of A.C. transmission.

Acceptance of A.C. was almost undisputed by 1890 and electrical engineers turned their energies toward developing bigger generator plants, the turbo-generator, and molding the theory for A.C. circuit analysis. Pre-eminent in the field of A.C. research were the two men, Professor Elihu Thompson and Doctor Charles Steinmetz, both of the General Electric Company. Professor Thompson invented such devices as the constant current-transformer, recording watt-meter, repulsion motor, resistance welder, and contributed much to the science of transformer design. Doctor Steinmetz deceived many with his diminutive, deformed body, but did not conceal from the world a brilliant mind that developed our present methods for the solution of A.C. problems, contributed much to the design of A.C. machinery, and later developed the first high voltage laboratory for simulating lightning strokes. As the size and efficiency of operation of the larger plants increased, more and more small industries that formerly operated small generating units of their own discovered power could be purchased more cheaply from electric power distributors. Large power transmission systems then grew rapidly and the first of these to be operated in the United States was the Willamette Falls to Portland, Oregon, system in 1890. Originally two alternators rated at 1250 lights and 4000 volts constituted this plant. Other hydro plants appeared in Southern California in 1892 and at Niagara Falls about the same time. Likewise turbo-alternator plants made their first bid to power in 1898, some 16 years after the Swedish scientist, Gustaf De Laval, built his first turbine. Previously in 1889 Westinghouse had already built the first 5000 hp., 2 phase, 25 cycle generator. By 1901 General Electric Company had built a large turbo-generator of 1500 kw capacity.

Further elaborations on equipment, increased sizes in hydro and steam units and transmission grids became products of the 20th century. By 1908 the first 100,000 volt long-distance transmission line had been installed. With the propagation of complex transmission systems there followed the concomitant problems of stability, high voltage circuit-interruption and protection, and methods for reactive supply. One solution for the latter problem was the synchronous condenser, which provides quite a little story of its own.

Chapter I

Evolution of the Synchronous Condenser

Although Thomas Davenport built the first commercial electric D.C. motor in 1837, time lapsed until 1873 before men recognized that a D.C. motor could also perform as a generator. It was during the demonstration of electrical transmission at Vienna in 1873 that the Belgian scientist, Zenobe Gramme, suggested D.C. motors could operate as D.C. generators. The same relationship as for D.C. machines was recognized for A.C. machines in 1884 by Doctor John Hopkinson in London. However, immediate development and production of synchronous motors was retarded by lack of an economical and practical device for bringing the motor up to synchronous speed. The invention of the induction motor by Tesla in 1887 furnished the solution for putting synchronous motors on a commercial basis. Small induction motors were utilized to bring the larger synchronous motors up to operating speed. The first installation of this nature is attributed to the Westinghouse Company at Telluride, Colorado, in 1890 where a 100 horsepower, 3000 volt synchronous motor drove the mine's ore crushing machine. At about the same time the General Electric Company began its production of synchronous motors.

Like all innovations the debut of the synchronous motor met with skepticism from some conservative engineers and evoked many involved discussions at technical meetings. It was at one such meeting of the American Institute of Electrical Engineers in April, 1893, that engineers received their first hint of the condenser characteristics of the synchronous motor. During the discussion of a paper presented by A.E. Kennelly, Steinmetz alluded, " A synchronous motor at certain conditions of excitation acts like a condenser (capacitor) of very large capacity." (10, p.229).

In the following year Doctor Louis Bell presented a paper on polyphase apparatus (2, p.33) which again stimulated protracted discussion on the synchronous motor. Apparently, many considered the synchronous motor futile because it was not self-starting. The induction motor displayed such large starting torques by comparison and had already demonstrated its ability under load conditions. William Stanley suggested, therefore, that induction motors be used for all power work but that synchronous motors might prove valuable to compensate for the lagging current in inductive loads. Steinmetz took issue with Stanley on this subject. With empirical facts to support his arguments he showed that synchronous motors were to be preferred to induction motors because of their constant speed, better efficiency, and beneficial effect upon line regulation. Evidently, these facts were very persuasive, for synchronous motors soon began to roll off the assembly lines, such as they were at that time. Synchronous motors surpassed the induction machine in performance for large jobs while induction motors have generally been preferred for the smaller tasks.

As Stanley pointed out, the synchronous motor could be used to supply leading current for transmission lines and so reduce line regulation and losses due to a heavy lagging current component. He applied the principle very successfully on a lighting load that suffered from low voltages due to the line reactance. Thus, the synchronous phase-modifier or the so called synchronous condenser came into existence. It is nothing more than an over-excited synchronous motor running without load. As the transmission systems stretched their tentacles out in inextricable complexity, kvar transmission requirements relied increasingly more on the unique characteristic of the synchronous condenser. From 1900 on to the twenties synchronous condensers paralleled the growth in size and quantity experienced by all electrical machinery in general. Power capacitors appeared on the scene much later so that the synchronous machine commanded a monopoly in the field of reactive supply for the first quarter of the 20th century.

Although the kvar requirements of transmission systems demanded corrective measures to attain reasonable efficiency, the synchronous condenser early manifested some innate shortcomings. Its losses were high and like all rotating machinery required considerable maintenance. Engineers were loath to condemn the machine for these small defects but instead resolved to improve machine design. This they did by sealing the machine in a Hydrogen atmosphere. Hydrogen displayed the properties of low density and high thermal conductivity, which made it ideal for a cooling or circulating atmosphere within the machine. Moreover, the Hydrogen atmosphere reduced corona damage, oxidation, operation noise, and excluded foreign particles from the machine.

The first hydrogen-cooled machine was a 20,000 kva machine installed by the Appalachian Electric Power Company in 1928. Initial experience taught that the gas seals were difficult to make, especially with direct-connected exciters. (8, p.890-906). For some five years following, practice was to operate the exciters from separate prime-movers. There were improvements in the gas seals, water cooling systems, explosion proof shells, provisions for maintenance and inspection, and additions of a collector compartment for the particles from the rings and brushes. It was soon learned that higher gas pressures markedly increased the kva capability for a given machine.

In 1941 the Indiana and Michigan Electric Company installed a 25,000 kva synchronous condenser. At 1/2 psi the machine delivered 18,750 kva but at 25 psi it attained 25,000 kva continously. The most modern machines of today rate as high as 60,000 kva. By this time engineers also recognized the advantage of including the exciter in the same Hydrogen atmosphere. A normal 100 kw exciter delivered 150 kw in a 25 psi Hydrogen chamber. Incorporating a direct-connected exciter within the hydrogen tank is now a standard practice.

Power systems had expanded considerably by the twenties with the result that increased attention was devoted the problem of power limitations and stability of transmission systems. Steinmetz recorded one of the first articles on this subject in 1920. (9, p.1215) Synchronous condensers were then widely used and their beneficial support to stability was well appreciated. Opinion in the late twenties recommended synchronous condensers in either load or generating areas as beneficial to stability. Engineers averred that condensers in the generating area would add inertia and so retard instantaneous acceleration of the generators due to faults. Likewise, condensers in the load areas were avowed to add inertia there and so reduce instantaneous deceleration at the receiving end. Present theory opposes this line of reasoning. (4, p.1130-1138)

Further work to improve stability blossomed in the form of new high speed excitation systems. (7, p.1020-1027) During and immediately following fault conditions stability often depended upon maintaining system voltages. By employing exciters with high speed of response synchronous condenser output could be raised to several times normal before the maximum of the first swing, and so aid in stabilizing voltages. In 1930 the Ohio Power Company introduced the first electronic pilot-exciter and regulator for a 15,000 kva hydrogen-cooled synchronous condenser. Amplidyne exciter control appeared in 1939 on the Appalachian Electric Power Company. Thus, by 1940 these general conclusions on the operation of synchronous condensers had been drawn:

1. Electronic exciters showed excellent performance, but initial and tube replacement costs precluded their extensive use.
2. 900 RPM was to be preferred to the higher operating speeds.
3. Hydrogen pressures of 15 psi would prove a very worthy investment in the larger machines.
4. Direct-connected exciters excelled in performance if placed within the machine's gas-tight jacket.
5. Electronic and amplidyne exciters had nearly the

same speed of response for small voltage changes.

6. Amplidynes could be used for lagging boost where the electronic exciters could not.

Like the many other facets of our scientific world time and man in the field of electrical machinery have accomplished marvelous strides on the road to progress. From the conception of the electrical machine to its existing mammoth descendants of today this chapter has traced the basic steps in the development of the synchronous condenser. The present models deviate from the ideal by far, but they do shine with a luster of perfection and efficiency little dreamed of in the early days. To what degree of excellence engineers will develop this device will depend significantly upon the value of its application, the competition from devices capable of performing the same tasks, and the complexity of the technical problems involved. Perhaps its value will be augmented by such applications as the one proposed in this thesis. Regardless, engineers are more concerned with the problem at hand and its best remedy than they are concerned with the industrial trends and historical significance of their inventions. It is then the reasons and applications for the synchronous condenser to which we revert our attention in the next chapter.

Chapter II

Power-Factor Control

Synchronous condensers are by nature only a transmission implement. They are not used to perform useful work like motors, but they display the same current-phase angle-excitation relationship as for the synchronous motor, shown below. The motor characteristic shows

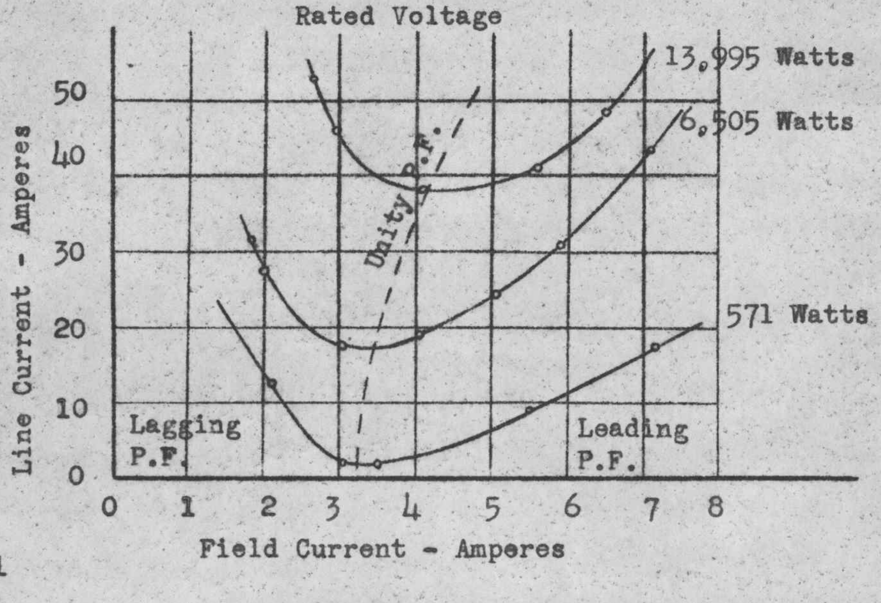


Fig. 1

Westinghouse Synchronous Motor
15 Hp - 220 V - 34 Amp. - Unity P.F.
3 Phase - 60 Cycle - 1200 RPM
Excitation - 125 V - 5 Amp.
Ser. No. 1-4N687

over-excitation produces a leading phase angle and, hence, a basis for the appellation, synchronous condenser. By means of field control the synchronous condenser input can be governed for the desired amount of leading or lagging phase angle current. In transmission parlance the synchronous condenser becomes a source or "sink" of kvar, which pumps or absorbs reactive power as required for the purposes of electric power transmission. Its primary function on most large power systems remains power-factor control. High values of power factor, usually above .95, are indispensable to economic operation of a transmission system. Otherwise low power factors require abnormally high generator kva ratings to supply a given load and so do not effectively utilize the current carrying capacity of the generator's windings. Moreover, other line equipment, such as transformers and regulators, require similar exaggerated ratings to carry moderate loads, if the power factor is low. Since the maximum load capability of transformers, generators, and small distribution lines is determined by maximum current carrying capacity, high p.f. operation is imperative to most effectual utilization of equipment ratings. Power contracts often incorporate bonus and penalty clauses to the effect that high p.f. be maintained by the customer. Low p.f. operation not only increases transmission losses, but it diminishes the useful power which the transmission grid and generating plants can deliver within their ratings and aggravates the voltage-control problem.

A simple example will lucidly convey these points: Assume that it is desired to supply a 100 mw load at the receiving end in the circuit below at a receiving-end voltage of 13.8 kv after transformation. To illustrate the effect of p.f. on voltage regulation, load current, and transmission line losses the following graph was prepared with the load real power constant at 100 mw and $V_2 = 13.8$ kv. The graph was compiled with the aid of the modified Evans and Sels transmission line charts appearing in the appendix.

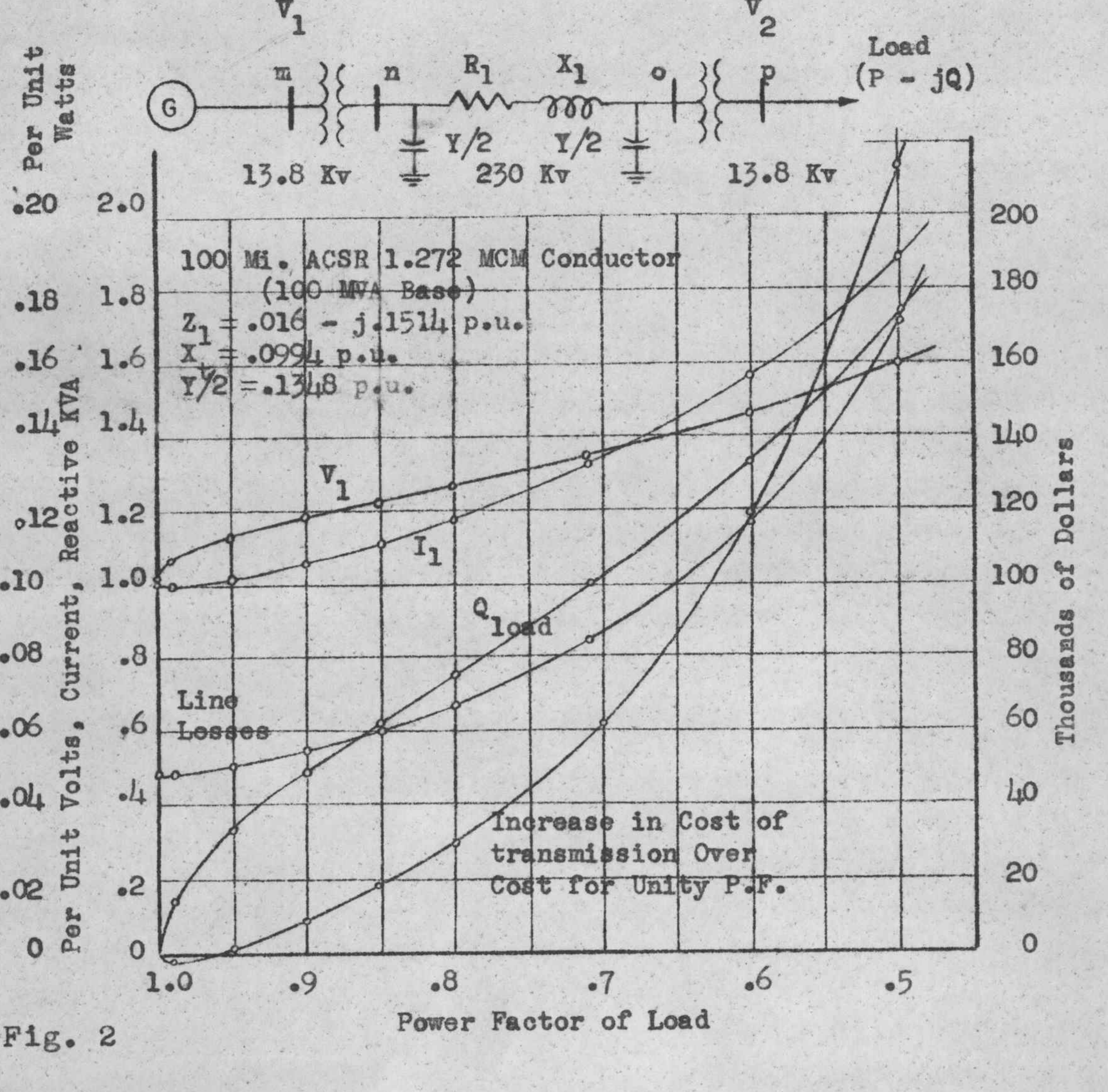


Fig. 2

At even 99% power factor the reactive required is already 14% of the real power and, thence, increases very rapidly until 95% power factor. From 95 to 60% p.f. the load reactive power is almost a linear function of the load's p.f., but approaches infinity at lower and lower p.f. Likewise, the sending-end voltage shows a marked increase, although almost linear except for the region near unity p.f. From unity to 60% p.f. V_1 must rise 43.5% in order to supply the given load. On the transmission line the sending-end would require about 303 kv line-to-line voltage to supply this load. In addition to problems of excessive regulation, added insulation requirements, and the need for greater generator capacity to supply the load kvar, the line current also climbs rapidly as the p.f. decreases. Not only does this burden the line and transformer nearer their capacities, but magnifies the transmission losses by the square of the current. The parabolic variation of losses with p.f. appears clearly on the graph. The initial dip in current, power loss, and incremental-loss cost results from the small line charging current which, when viewed from the generator, appears like a leading current load for unity p.f. load at the receiving end.

Obviously, the transmission system suffers tremendous financial losses if continuous operation at low p.f. on long lines is permitted. Any transmission power losses amount to a direct cost to the transmission company at the prevailing market price for electric power, since that power represents vendible power and a potential source of revenue, if the market for electric power is greater than the generating capability. One curve on the preceding graph illustrates the increase in cost / yr. for losses above that for unity p.f. load. A present market price for electric power in the Northwest of $17.50 kw/yr. and unity yearly load-factor is assumed, and transformer losses are not included. A 60% p.f. indicates an increase in cost above that for unity p.f. of 119,600 dollars or an increase of 239%. The inefficiency of low power-factor operation, then, presents a formidable financial objection in itself.

Inordinate voltage regulation, as displayed in the example at low p.f., augments insulation costs on line, transformer, arresters, and other attached apparatus. On the other hand, higher transmission voltages increase the line charging current and so tend to offset the line's reactive current. Voltage fluctuations become untenable as the load p.f. undergoes sporadic changes if the line impedance is high and a low p.f. already exists. For these reasons engineers design lines for minimum impedance and strive for a minimum of reactive power on the line.

Of course, both real and reactive current components produce a potential drop along the line, but due to the vector relationship the reactive component induces the more severe line drop component. This phenomenon is illustrated in the vector diagram below for a 70.7% p.f., 100 mw load and the transmission line of the foregoing example:

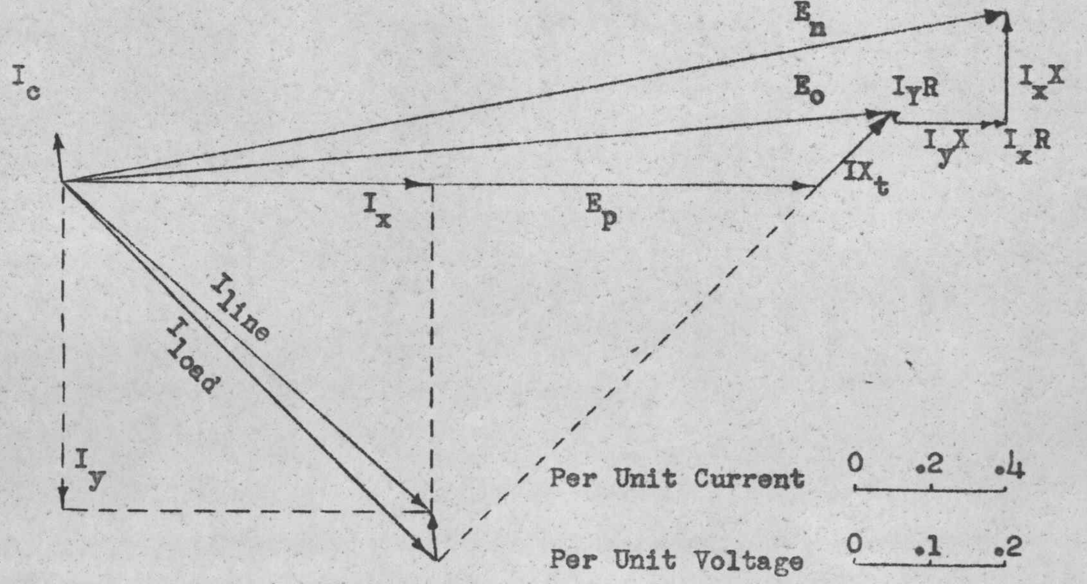


Fig. 3

In order to illustrate the relative significance of the reactive component of current on the line the actual current reactor is resolved into its two mutually quadrature components, I_x and I_y. The small line charging current leads the voltage E_o by 90^o and subtracts from the lagging load current, as shown. The resultant line current components produce both resistive potential drops of nearly equal magnitude and reactive potential drops of nearly equal magnitude. However, the reactive component of line current significantly induces a drop in the line reactance which nearly adds in phase to the receiving-end voltage while the real component of current creates a potential drop due to the lines reactance approximately 90° out of phase with the receiver voltage. Since inductive reactance constitutes the major portion of power transmission line impedance in the usual case, the reactive component of current is observed to be the most detrimental to preserving a minimum sending-end voltage. Although the in-phase component of current produces a sizeable inductive drop it adds to the receiver-end voltage in such a manner as to increase the sending-end voltage comparatively little.

Clearly, the objections to low p.f. operation are well rooted in fact and logic, and engineers well appreciate the services of synchronous condenser to remedy the situation. Of course, static power capacitors would perform the same task, and more about these will be related in later chapters. A synchronous condenser or capacitors placed at the load in the following example would have cancelled much of the lagging component of load current, relieved line, transformer, and generator conductors of current burden, lowered sending-end voltage and, in the case of the synchronous condenser, would have provided automatic compensation for changes in load voltage. It is convenient that the synchronous condenser usually appears on the load side of the transformer, necessitated by normal synchronous condenser and capacitor voltage ratings, for the transformer also experiences an improvement in p.f. and a reduction in losses. Transformer regulation is also improved by raising its p.f. (6, p.205)

Chapter III

Voltage Regulation

In most large electric power pools seasonal and diurnal load changes impose voltage problems which require special engineering attention. Initially transformer taps are set to provide the desired voltages for the expected average load. On the low voltage distribution feeders automatic transformer tap-changing devices and induction voltage regulators assist in maintaining constant voltages. Where industrial loads experience great load and power-factor changes as between mid-day load and nightly shutdowns, manually or automatically controlled shunt capacitors may be employed very advantageously to stabilize voltages and improve transmission power-factor. The improvement of power factor near the load is felt far back into the system, for if the sources of generation are required to supply the load's reactive power, more line drop will occur all along the feeders between source and load. At the higher voltage substations a similar condition exists; any reactive that is required by loads emanating from that substation should be supplied at that sub and not by the generators, if fairly constant voltages and reasonable line losses are to be secured. Often times the subs or areas are deficient of kvar supply, and the generators have to supply the load's reactive requirements. A 1949 study of the Pacific Northwest Power Pool indicated that power factor varied sufficiently to require 10% more kvar at the substations during the forenoon hours than was required to maintain approximately constant voltages during the evening hours, assuming constant real power loads. Then, too, several lines may be energizing the sub and only a proper relation of taps and phase angle on the transformers will equalize the reactive load on each line and so help to stabilize voltages. Thus, the maintenance of constant voltage levels demands accurate coordination between transformer-tap settings and reactive supply in the load areas. Finite blocks of static capacitors may be switched to supply the increment in kvar required, and then again, a synchronous condenser has certain inherent advantages for this task.

Aside from its ability to draw leading current, the synchronous condenser and motor possess another interesting characteristic, peculiar to themselves but very applicable for transmission voltage problems. By virtue of the characteristic shown in Fig. 4 the synchronous machine endeavors to automatically compensate for any changes in voltage at its terminals. We are reminded from the first chapter that Dr. Steinmetz pointed out this inherent regulating feature of synchronous motors as early as 1893. For any constant field current it is noted that a reduction in terminal voltage causes the power factor to become more leading and any increase in terminal voltage results in a more lagging power-factor. Since a leading current tends to raise the

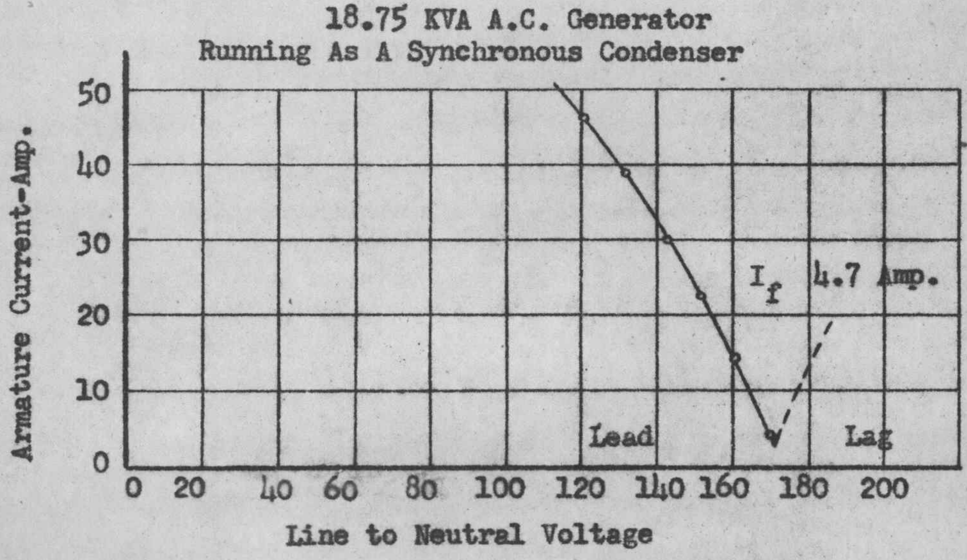


Fig. 4 Synchronous-Condenser Characteristics

receiving-end voltage while a lagging current lowers the receiving-end voltage on a transmission line the synchronous condenser attempts automatically to compensate for system voltage fluctuations. It, therefore, can be and is utilized as a voltage regulating device to stabilize receiving-end voltages. Because this action to oppose any voltage change is smooth and completely automatic, it can be relied upon where the voltage changes are too small to require switching capacitors, where voltage changes are within the dead band of the condenser's voltage regulator system, or where the voltage change occurs too suddenly for the excitation system to act. Usually, the condenser increase in output of its own accord during a voltage depression condition is too small to materially affect voltages in a large system. Consequently, most large condenser installations employ voltage regulators which boost the output more rapidly and in greater proportion than would be occasioned by normal condenser action. To imbue a perspective of the magnitudes involved in normal condenser operation consider the following empirical data derived from a 18.75 kva synchronous machine running as a synchronous condenser.

The following synchronous machine was employed for all experiments in this thesis except where otherwise stated:

General Electric A.C. Generator

15 KW .8 P.F. Cont. 50° C Rise

Model 12G 88 Type ATI

3 Phase 60 Cycle 18.75 KVA

240 Volts 45 Amps. 1200 RPM

Exc. 125 Volts 4.7 Amps.

Ser. No. 5663567

Per unit quantities appear usually in order to extend the discussion to include all machines, regardless of size.

Typical synchronous condenser constants are listed below for comparison with the test machine used. Derivation of test machine constants appears in the appendix. Values

	$x_{d_{un}}$	x_d'	x_d''	x_p	$r_{d.c.}$	T_d'	T_d''	T_a
Typical Values	1.80	.40	.25	.34	.002-.015	2.0	.035	.17
Test Machine	.990	.221	.100	.168	.026	.046	.011	.024

(Base is 18.75 kva, 240 volts, $240^2/18,750 = 3.075$ ohms.)

Fig. 5 Comparison of Synchronous-Condenser Constants

are in per unit or seconds, and since $r_{d.c.}$, the armature D.C. resistance, varies greatly with machine rating, the typical values are for 50,000 kva and a 500 kva machine. Any conclusions drawn from the experimental results should be modified by the fact that the test machine constants above are considerably smaller than those for the customary large machines.

To illustrate quantitatively the regulation phenomenon suppose the condenser operated at rated field and terminal voltage. For a 10% reduction in steady-state terminal voltage and for the same excitation the previous curve

	Per Unit		
	I_f	E_t	I_a
Initial Condition:	1.0	1.0	.727
E_t depressed 10% :	1.0	0.9	.972

on page 26 provides the old and new current output. Thus, a 10% depression of voltage produces a 33.8% increase in leading current which would tend to raise the terminal voltage. Similarly, a 1% depression of voltage engenders a 3.4% rise in armature current. Also, the case can be extended for rises in terminal voltage which in turn would reduce the armature current, again in such a direction as to stabilize voltage. Although the innate increase in output current is small for small depressions in voltage in the steady-state, significant increase will be shown to occur under transient conditions because of the low ratio of x_d'/x_{d_s}. For the transient case inherent synchronous condenser action alone produces the initial large rise in current, because the exciters require some time to act. For the steady-state, however, there exists no doubt that a moderate-rate-of-response excitation system is desirable for the following reasons:

1. The excitation can be boosted or lowered over a wide range to change the output not just 3 or 34%, but say, 100 to 200% and so, contribute a measurable amount to the stabilization of voltages.
2. Moderate rate-of-response excitation control systems can act before voltage dips or peaks cause noticeable effect to industrial or lighting loads.

Common exciter response for synchronous condensers varies about the figure .5, which means the exciter can raise its voltage by 50% within one second. Higher speed of response can be attained but at a cost varying almost linearly with the rate of response (12, p. 630). One such high speed system requires only 25 cycles to raise the output of a synchronous condenser from 10,000 to 55,000 kva (11, p.315-318). As implied above, however, very high response exciters do not have sufficient advantage over normal exciters to warrant their use solely for steady-state voltage correction. Exciters with high rates of response originally were developed to maintain high internal voltage on the machine. This improves transient stability limits of which more will be said later.

Chapter IV

Theory and Analysis of Steady-State Synchronous-Condenser Problems

What are the enigmatic processes by which a machine teeming with coils and inductive circuits can behave like a simple capacitor? This question undoubtedly disturbs many at first but has a rather clear physical explanation in the magnetic fields involved. Two distinct seats of magneto-motive-force exist in the synchronous motor or condenser. First, the application of polyphase alternating voltage to the armature coils produces a constant rotating field. Secondly, the D.C. poles of the rotor field supply another rotating field which rotates in synchronism with the applied armature field. The interaction of these two rotating fields produces motor action and explains why a plain synchronous motor is not self-starting. The sum of these field fluxes sweeping across the armature conductors induces a back electro-motive-force in them. The vectorial difference between the impressed voltage and the induced back e.m.f. is, then, the e.m.f. which circulates the required armature current through the machine's inductive impedance. If the induced back e.m.f. exceeds the impressed voltage, as per high field excitation, then the synchronous motor wants to perform as a generator with an internal voltage greater than the terminal voltage of the network to which it is immediately attached. Since, the motor has no prime-mover it cannot supply power, and, therefore, must draw a demagnetizing component of armature current from the line to establish equilibrium. The demagnetizing component of armature current leads the voltage drop across the machine and corresponds to synchronous condenser action as will be explained.

A cylindrical-rotor generator with lagging power-factor connected to a system of constant voltage and frequency has this general vector diagram:

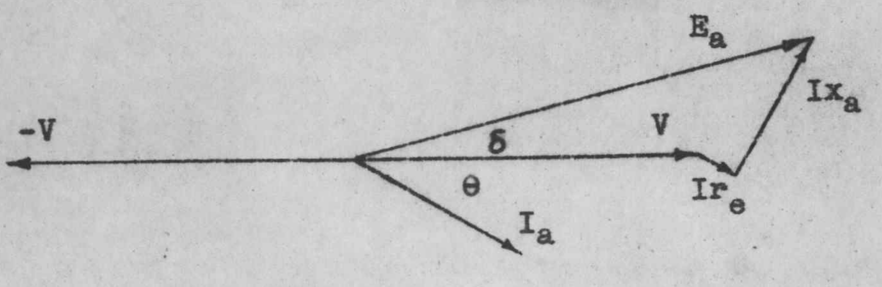


Fig. 6 Synchronous-Generator Vector Diagram

E_a = voltage rise induced per phase by net air-gap flux.

V = terminal voltage rise per phase.

$-V$ = terminal voltage drop per phase.

r_e = armature effective resistance per phase.

x_a = armature leakage reactance per phase.

I_a = armature current per phase.

θ = power-factor angle.

δ = power angle.

We note the power angle δ is positive and the air-gap voltage E_a leads the terminal voltage. If the power input to the generator drops, δ decreases in order to reduce the generator output and to re-establish a condition of equilibrium. Now, if the mechanical driving power is suddenly disconnected, the rotor frequency will momentarily slow down, δ will become minus or lagging, the real component of armature current will reverse (since power for machine losses must now come from the line), and the new equilibrium diagram will appear as below:

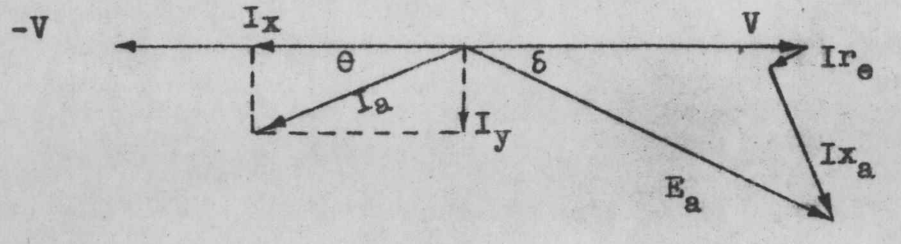


Fig. 7 Synchronous-Motor Vector Diagram

Now δ is negative, and the rotor poles lag the armature poles in time and space, which corresponds to motor action. The power-factor angle is read as the angle between the armature line current and the voltage drop or negative of the voltage rise across the machine per phase. The same over-excited condition as for generator action now produces a leading current component in addition to the power component in phase with -V. The total current taken from the line by the motor equals the ratio of resultant voltage to machine impedance, $(\bar{E}_a-\bar{V})/(r_e+jx_a)$. Suppose that the motor is running light like the normal synchronous condenser; then the armature has only a slight in-phase component of armature current to supply the machine's losses. Most of the current will be in quadrature as shown below, and E_a will be nearly in phase with the impressed voltage V.

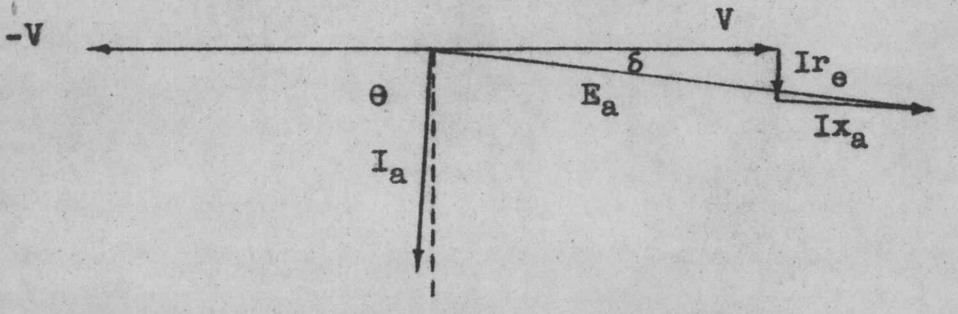


Fig. 8 Synchronous-Condenser Vector Diagram

Since the resistance drop adds perpendicularly to V and, therefore, effects the magnitude of E_a a negligible anount, the armature current can be approximated as $I_a = I_y = (E_a-V)/Z_a$. Because V and Z_a are essentially constant, I_a is nearly a direct function of E_a, the net air-gap voltage which, in turn, depends upon the excitation. The manner in which I_a varies with E_a is shown in the following locus diagram, determined from the vector diagram for varying values of E_a, a small constant power component of current ascribed to machine losses, and a constant displacement angle δ, which actually varies a little with excitation. The resultant voltage and armature current per phase are nearly at right angles at all times since the machine's reactive component of impedance predominates the resistance. However, the

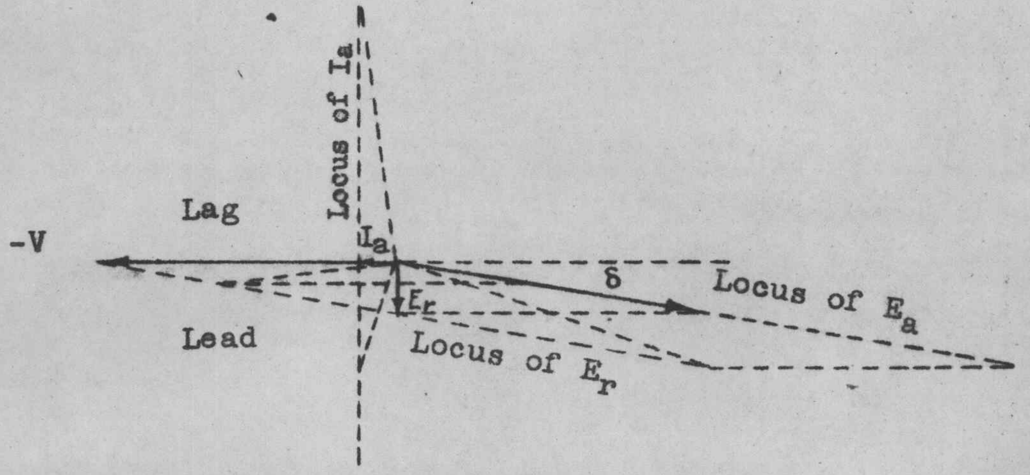


Fig. 9 Synchronous-Condenser Locus Diagram

magnitude of I_a and the power factor vary with the magnitude of E_a, becoming a lagging power-factor for low values of E_a and a leading power-factor for high values of E_a. Unity power-factor results when E_a equals V approximately. Hence, synchronous condenser action for leading current requires over-excitation to produce a back e.m.f. greater than the impressed voltage.

The above theory is born out by the familiar characteristic "V" curves of the synchronous motor, but it requires some interpretation for a quantitative analysis. Since E_a and V are nearly in phase for the synchronous condenser, the seats of m.m.f. and the armature and field poles must also be in time phase or in alignment.

However, the poles are opposing on over-excitation because the armature current was shown to be demagnetizing. This is illustrated in Fig. 10 for a hypothetical full pitch armature winding. Immediately the calculations for the salient pole synchronous condenser are vastly simplified, because the Two Reaction Diagrams will contain only direct-axis quantities; the quadrature-axis flux and current are too small to consider. The complete vector diagram, using saturated

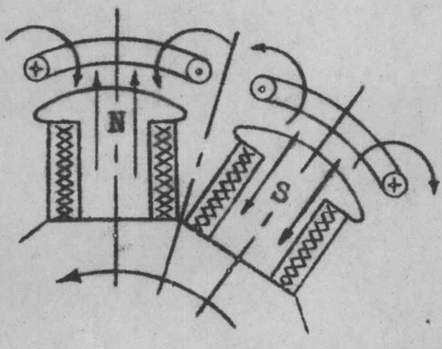


Fig. 10 Synchronous-Condenser Flux Pattern

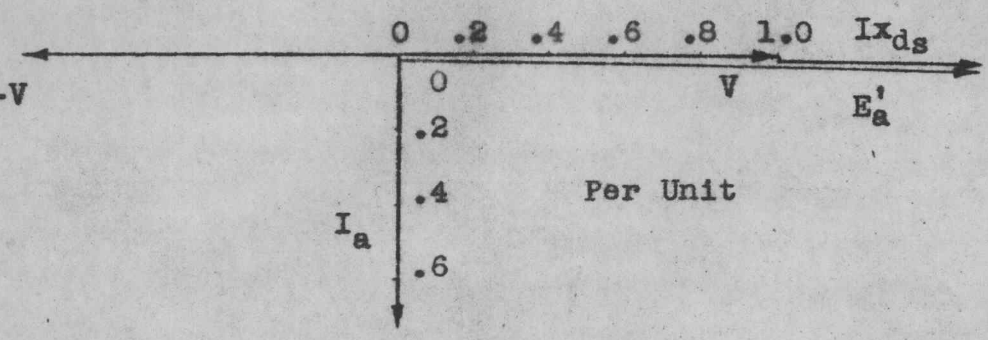


Fig. 11 Vector Diagram of Test Condenser

x_{d_s} = saturated value of direct-axis synchronous-reactance.

V = impressed voltage rise per phase.

E_a' = voltage due to the excitation or the voltage read from the load saturation line corresponding to a constant saturation, the same as for the condition of loading. (The load saturation line is constructed through the origin and the point on the open-circuit saturation characteristic corresponding to the net air-gap voltage or voltage behind leakage reactance for the particular condition of loading.)

values of synchronous reactance, is shown in Fig. 11 for a leading current at rated voltage and excitation for the test machine in the laboratory.

In the previous chapter the output current of the machine for certain impressed voltages and excitation was read direct from empirical machine characteristics. Usually those characteristics are not available and analytical methods employing only two common characteristic curves of the machine offer the only solution for determining unknown terminal quantities of the machine. The accepted A.I.E.E. method using Saturated Synchronous-Reactance will be exemplified here. From the open-circuit and full-load zero-power-factor saturation curves of the machine the value of Potier reactance is determined to be,

$$x_p = \frac{23.2 \text{ volts}}{45 \quad \text{amps.}} = .516 \text{ ohms} = .168 \text{ per unit}$$

on the machine's own base. R_e was measured and corrected to be $r_e = 1.6 \times .069 = .110$ ohms $= .036$ per unit. For most engineering purposes Potier reactance may be substituted for the armature-leakage reactance, even

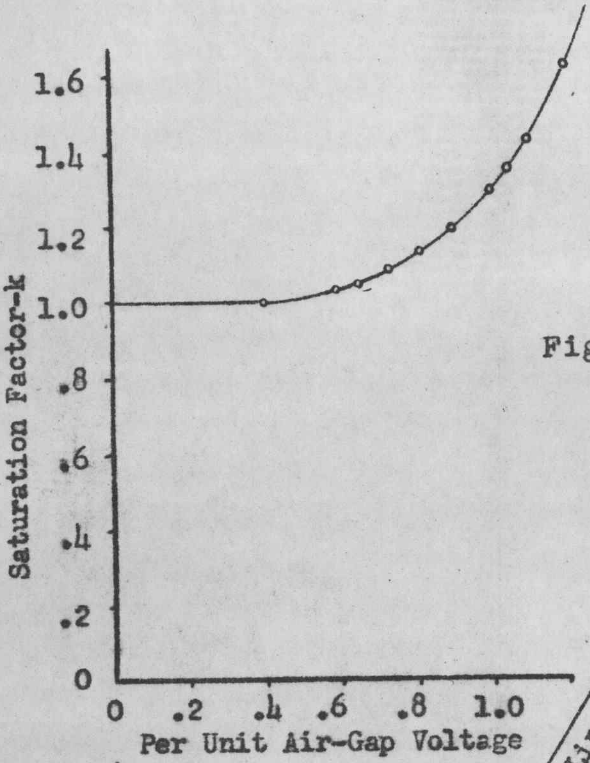


Fig. 12 Saturation-Factor Curve

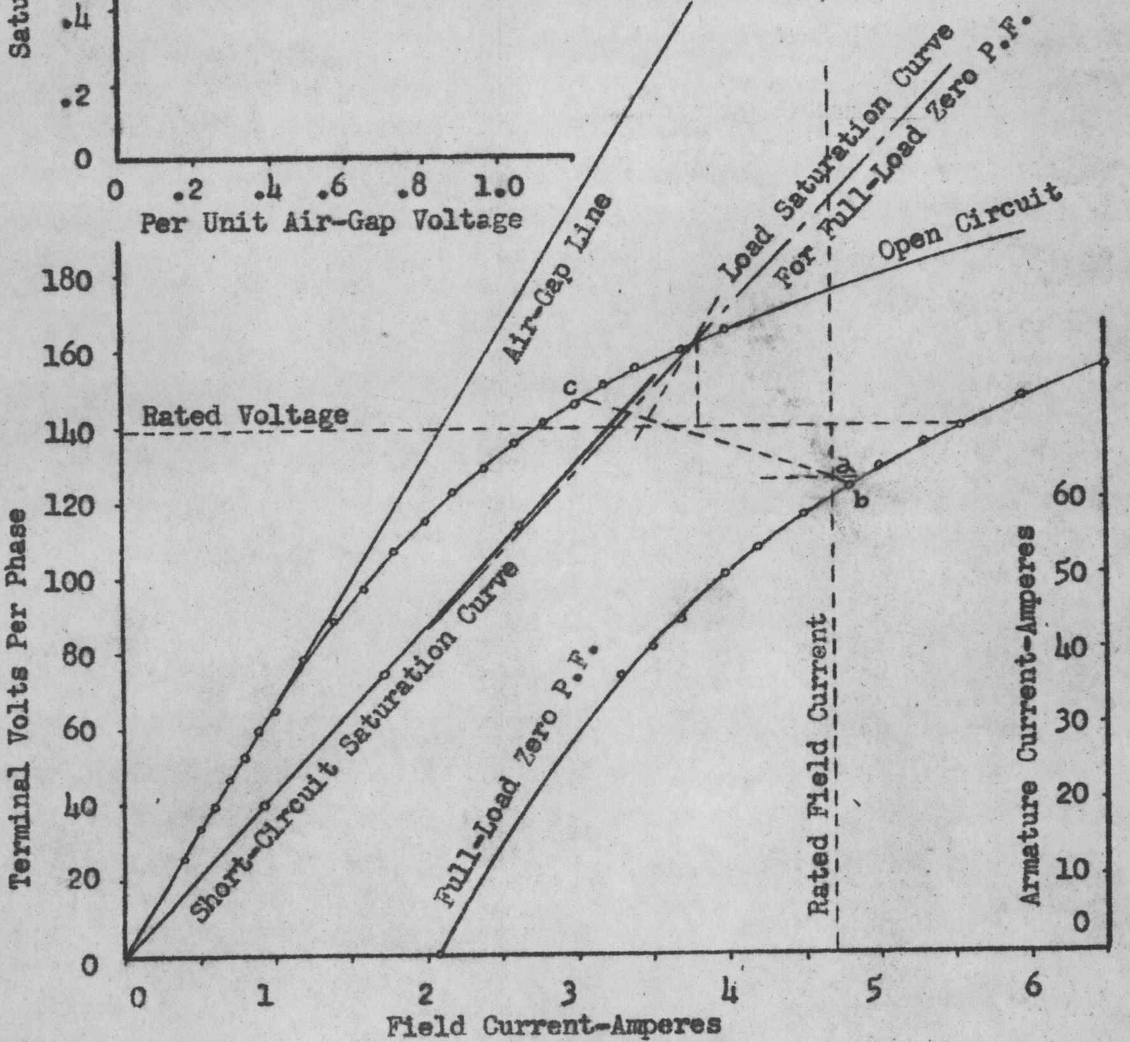


Fig. 13 Test Machine Saturation Characteristics

though Potier reactance is known to be larger and decreases considerably with saturation. The unsaturated value of synchronous reactance can be obtained easily from the short-circuit and air-gap lines for any constant field current: $x_d = \frac{173 \text{ volts}}{56.8 \text{ amps.}} = 3.041 \text{ ohms} = .99 \text{ p.u.}$

To correct for saturation it is assumed after the paper by P.L. Alger (1, p.493) that leakage reactance remains constant and that the component of unsaturated synchronous reactance due to the reactance of armature reaction, $(x_{d_{un}} - x_p)$, varies with saturation. An adjustment for $(x_{d_{un}} - x_p)$ takes the form of a saturation factor k, which is a function of the machine saturated air-gap voltage or open-circuit voltage. K is equal to the ratio of voltage on the air-gap line to the voltage on the open-circuit saturation characteristic for any particular field current. Thus,

$$x_{d_s} = x_p + (x_{d_{un}} - x_p)\frac{1}{k}$$

and the excitation voltage is

$$E_a' = V + I_d\,(r_e + jx_{d_s}).$$

The air-gap voltage is $E_a = V + I_a\, x_p$.

Let us attempt to check the measured set of terminal conditions in the previous chapter.

E_t = .9 per unit = 124.7 volts per phase

I_f = 1.0 per unit = 4.7 amps.

Except for a small correction due to the change in saturation the voltage E_a' set by the excitation will remain approximately the same, since the excitation has not changed. Assuming E_a' the same as for the initial condition then an approximate value can be calculated for I. This value can then be re-substituted in the formula for E_a, the air-gap voltage, and the value of field current checked from the load saturation line. From whatever error exists between the calculated and actual field current a new estimate for I can be made and similarly checked until the series of approximations results in the correct answer. If k did not depend upon E_a then the simple linear equation for E_a' would give the answer directly.

For the first approximation take the intersection of the ordinate through $I_a = 4.7$ Amps. and the horizontal line through V = .9 p.u. on the load saturation graph. The zero power-factor load saturation curve for the desired current must pass through this point. Since Potier reactance drop varies almost linearly with the armature current, the desired current can be approximated from a proportion involving the distances formed on the hypotenuse of the Potier triangle through the above point. Thus,

$$I_a = \frac{ac}{bc} \times 45 = \frac{23.6}{25} \times 45 = 42.5 \text{ Amps.} = .945 \text{ per unit.}$$

For many purposes this first approximation will provide sufficient accuracy. Test this value of I_a;

$$E_a = .9 + (.945) \times (.168) = 1.059 \text{ per unit}$$

$$k = 1.37 \text{ (from saturation factor curve, Fig. 12)}$$

$$x_{d_s} = .168 + (.990 - .168)\ \frac{1}{1.37} = .768 \text{ per unit}$$

$$E_a' = .9 + (.768) \times (.945) = 1.625 \text{ per unit}$$

$$E_a' = 225 \text{ volts}$$

When E_a' is plotted on the load saturation line through the origin and $E_a = 1.059$ on the open-circuit saturation curve, I_f is read as 4.67, just a little low. Hence, try $I_a = 43.7$ amps $= .972$ per unit.

$$E_a = .9 + .972 \times .168 = 1.063 \text{ per unit} = 147.2 \text{ volts}$$

$$k = 1.38$$

$$x_{d_s} = .168 + (.990 - .168)\ \frac{1}{1.38} = .764 \text{ per unit}$$

$$E_a' = .9 + .972 \times .764 = 1.642 \text{ per unit} = 227.6 \text{ volts per phase.}$$

This value of E_a' gives $I_f = 4.7$ amps. Therefore, $I_a = 43.7$ amps $= .972$ per unit is the true armature current for rated field current and 90% rated terminal voltage. This checks very well with the value of $I_a = .972$ per unit in Chapter III.

So far the discussion has reviewed and unfurled the usual and primary application, the important characteristics and theory, and the analytical approaches to the solution of steady-state problems for the synchronous condenser. With this preliminary background we wish to turn now to the objective of this thesis, which is the investigation of machine performance with series-capacitor compensation for machine reactance.

Chapter V

KVAR Supply During System Transients

Both steady-state and transient stability limits are significantly improved in a large power system by distributed synchronous-condenser capacity. The aid to stability evolves from the support provided system voltages, provided the support does not lower the generator excitations greatly (5, p.291). Application of synchronous condensers at intermediate points of long transmission lines to raise the power transmission limits has been proposed but denied realization, because marginal benefits do not justify the cost. Instead, system interties on long lines accomplish the same task as a large synchronous condenser. At major points of interconnection the controlled synchronous supply of kvar is necessary to stabilize voltages, as discussed earlier. The synchronous condenser excels in this function because light loading may often require lagging capacity. A.C. Network Analyzer studies have shown, however, that one such condenser has little effect upon system stability during transient swings and that only a prodigious supply at one interconnection point or many distributed sources of kvar will influence system stability (4, p.1130-1138). We, therefore, conclude that any device capable of injecting abnormally large packets of kvar into the system during transient conditions still will probably not justify its existence unless used at several or more points of the system. The system in mind consists of interconnected load areas, each with some generation, but probably insufficient amounts to supply their own needs without the transmission of power from other generating plants outside that area.

Let us digress now from the generalities of the phrase, "transient stability limits," and consider the physical conditions accompanying the fault. Initially, a fault on the major transmission grid suppresses loads by lowering voltages. The generators near the fault speed up because of the unbalance of input over output power to the generator. Any capacitors in the fault area also drop in output, thereby, lowering voltages more and dropping still more load. Obviously, this is bad for customer service, but beneficial to stability, because both sets of machines, those in the load area and the external machines supplying the large transmission grid, will tend more to accelerate together and remain in step; both groups of machines have lost load. Now, any synchronous condensers in the load area support voltages even more than usual during fault and low voltage conditions, and this causes the loads to hang on. Consequently synchronous machines in the load area do not accelerate as rapidly as the external machines, and the two sets of machines start to wind apart. The issue of synchronous condensers in load areas has been treated at length and has been labeled malicious to stability, especially, if the condenser is large or has a very low transient impedance. Even if fast fault clearing times exist, any support to voltage in the load area immediately after clearing of the fault can only reload and retard both groups of machines, with the probable event of loading the retarded machines in the load area greater by proportion than the main machine groups of the major system. In particular, this will be the case if the main machine groups possess more inertia than the machine groups in the load area, for the small machines will retard more quickly.

Synchronous-condenser capacity at major points of inter-tie on the 230 kv grid cast a somewhat different influence upon system stability. By way of illustration, refer to the actual system in figure 14. The Midway condenser is such a condenser. For a fault on the link between Coulee and Midway at C, the condenser will support voltages, holdup loads, and cause the rest of the system to decelerate while Coulee accelerates. This action is partially offset by the tie to Columbia which tends to load heavier than normal, and so once the faulted line is

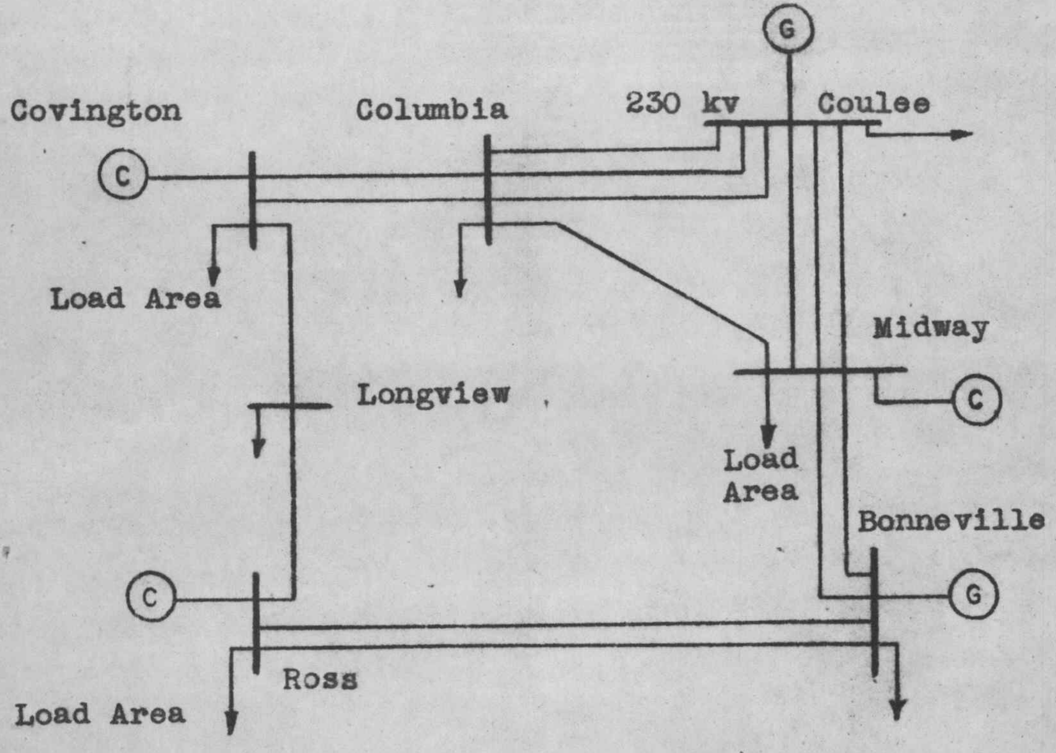


Fig. 14 Pacific Northwest Major 230 Kv. Transmission Grid

opened, tends to retard Coulee generators a little. However, without this tie— say, if the line relays out— the Condenser at Midway would undoubtedly augment the angular separation between Coulee and the remainder of the system and so jeopardize chances for recovery. With this tie in the condenser does not have to great an effect upon stability, but it has been found in stability studies at BPA that any increase in kvar from this condenser while the fault is on definitely lowers the stability limit (3, p.30). On the other hand, once the fault is cleared any increase in kvar supply at Midway rapidly boosts the loading and immediately retards the acceleration of Coulee. Stability is improved by this operation. In this case interconnected loads at Midway tend to slow Coulee down more percentage-wise than the increase in loading in other areas retards the other machines. Careful studies would be in order for each actual system to determine the consequence of injected kvar immediately after clearing of the fault. Past studies indicate that systems with few interconnecting lines stand to suffer from any kvar supplied in load areas or even at points of inter-tie if the support to voltages and loads does not effect all groups of machines uniformly. With many inter-ties all machines experience nearly equitable effect from kvar supply, during the fault, except for machines isolated from the system by bus faults. Heavy inter-ties favor a more uniform elevation of voltage and loads in all areas, which in turn, inclines the machine groups to retard more as a group, thus, minimizing the chances for some groups to pull away. This tends to corroborate the statement that <u>individual</u> synchronous condensers at points of inter-tie have little effect upon stability (5, p.291).

It was conceived that considerable aid to stability could be obtained by forcing excess kvar into the system at major points of inter-tie immediately following a fault. The boosts to voltages in general are speculated to increase stability limits and at the same time promote a uniform distribution of load following the fault, so that no one machine group is hit too severely. In another respect, the increase in kvar resembles the stiffness provided the system by a huge synchronous condenser. We recall the rapid response exciter systems for synchronous condensers promoted during the late twenties and during the thirties and the appraisal given low reactance or unusually large condensers. Since then some revision of thought has become apparent, for analyzer studies have conclusively shown the error of introducing kvar during the fault. With this in mind there remains the possibility of pumping kvar into the system immediately after the fault, and this suggestion possesses valid analyzer studies and logic in its favor.

One A.C. Analyzer study of the system shown compared the effects of a normal 120 mva synchronous condenser at Midway loaded to 90 mva initially with the same condenser compensated in 8 cycles (3, p.50). The fault was placed at Coulee on two Coulee-Midway lines which cleared at both ends in 8 cycles. Both cases were stable and identical until the 8th cycle, when the condenser received series-capacitor compensation for x_d' in the second run. Some of the pertinent data appears in Table 1 on the following page:

Table 1

Run #1: 120 mva synchronous condenser, initially loaded to 90 mva; initial terminal voltage = V_t = 1.15.

100 Mva Base

	Cycles	Mvar Output	V_t	θ Angular Separation of Bonn and Coulee
(Faulted)	0	-----	-----	43°
	4	-----	-----	48
(Cleared)	8	-----	-----	61
	12	1.084	1.006	78
	16	1.150	.932	91.5
	20	1.250	.868	100.5
	24	1.250	.830	105.0
	28	1.250	.822	104.0

Run #2: 120 mva synchronous condenser, initially loaded to 90 mva and V_t = 1.15 per unit. x_d' compensated 50% at end of 8 cycles.

	Cycles	Mvar Output	V_t	θ
(Faulted)	0	-----	-----	43°
	4	-----	-----	48
(Cleared)	8	-----	-----	61
	12	1.860	1.079	78
	16	2.030	.994	91.5
	20	2.135	.946	100.5
	24	2.185	.905	104.5
	28	2.200	.894	104.0

Run #3: 120 mva synchronous condenser, initially loaded to 90 mva and V_t = 1.15 per unit. x_d' compensated 90% at end of 8 cycles.

	Cycles	Mvar Output	V_t	θ
Faulted)	0	-----	-----	43
	4	-----	-----	48
(Cleared)	8	-----	-----	61
	12	3.760	1.210	77.5
	16	4.175	1.143	90.5
	20	4.420	1.105	99
	24	4.740	1.087	103
	28	4.630	1.076	101

The study assumes all internal voltages remain constant over the interval involved. Normal Midway bus voltage is 1.15 per unit on a 200 kv base. Most notable is the 10 to 20% improvement in voltage at Midway for the case of the compensated condenser. The improved voltage in Run 3 retarded both machine groups but decelerated Coulee more rapidly than Bonneville. The net result was a decrease of the maximum angular displacement between the main two machine groups, Coulee and Bonneville. Condenser output for 90% compensation climbed to over 5 times its initial loading, which might prove to be to heavy a jar for an ordinary machine. Actually with 90% compensation we would expect even a more violent jolt, if the bus voltage had reduced to 1.006 as it did in Run 1:

$$E_d' = V_t + I_{ss}(x_d' + x_T) = 1.15 + \frac{.90}{1.15}(.371 + .062)$$

$$E_d' = 1.489 \text{ per unit.}$$

(If the output is measured at the bus,)

$$i'_d = \frac{E'_d - V'_t}{x'_d + x_T - x_c} = \frac{1.489 - 1.006}{.371 \times .1 + .062} = \frac{.483}{.097} = 5.0 \text{ p.u.}$$

Expected mvar output = 5 x 1.006 = 5.03 = 503 mvar.

Evidently, the effects of compensation in nearly all real cases will be partially nullified by the improved voltage at the condenser bus, which then reduces the output below what would be expected if the condenser were connected to an infinite bus. The nullifying effect is not too great, however, but some deliberation should be allowed this point in design. Quite apparently, the system is more stable when excess kvar enters the system following the fault. How much more rigid the system is, or what new power limits could be attained with stability under this operation of the condenser will require further studies. We did notice that nearly doubling the condenser output by compensating 50% had negligible effect upon the angular separation, but the improved voltage would allow more angular separation without losing step.

To boost the reactive generation during fault conditions does not reduce to the single method applied in the previous study. Actually, we might employ any of the following methods:

1. Super-rated condensers, normally only partially loaded.
2. Low reactance condensers.

3. Ultra-high speed excitation systems.

4. Added banks of capacitors.

5. Capacitor banks switched from wye to delta.

6. Series-capacitor compensation for synchronous-condenser reactance.

In all cases except numbers 1 and 2 the large increment in kvar output could be delayed until clearing of the fault. Methods 1 and 2 have one point against them on this account. Quantitatively, the practicable instantaneous output current that could be realized by each case, neglecting subtransient effects, compares as follows:

(All calculations are on a 50 mva base.)

Assume $V_t' = .9$ per unit and initially $V_t = 1.0$ p.u.

<u>Case 1 Normal condenser:</u>

50 mva, $x_d' = 40\%$, 13.8 kv.

$E_d' = 1.0 + 1 \times .4 = 1.4$ per unit

$i_d' = \dfrac{E_d' - V_t}{X_d'} = \dfrac{1.4 - .9}{.4} = 1.25$ per unit.

<u>Case 2 Super-rated condenser:</u>

100 mva, $x_d' = 40\%$ on own base

$x_d' = .40 \times \dfrac{50}{100} = .2$ at 50 mva

$E_d' = 1.0 + 1 \times .2 = 1.2$ per unit

$i_d' = \dfrac{1.2 - .9}{.2} = 1.5$ per unit

<u>Case 3 Low reactance condenser:</u>

50 mva, $x_d' = .2$

$E_d' = 1.0 + 1 \times .2 = 1.2$

$i_d' = \frac{1.2 - .9}{.2} = 1.5$ per unit

<u>Case 4 Ultra-high speed excitation:</u>

Even the fastest excitation systems require .1 seconds to produce any noticeable change in condenser armature current, and we recall 25 cycles were required to raise the output of one such condenser from 10.000 kva to 55,000. In 10 cycles about twice the initial current might possibly be attained, but only if the condenser were initially only partially loaded or had a very substantial field winding, that could endure the forcing voltages and current. Such excitation cannot be obtained cheaply but has no physical limitation which prevents it from boosting condenser output to values comparable with those of these other methods and almost the same amount of time.

<u>Case 5 Added capacitors:</u>

The addition of an added bank of 67.5 mva of capacitors would be necessary to obtain 2 p.u. current on 90% voltage, if a 50 mva condenser were already in service.

$i_d' = 1.25$ per unit $\qquad i_c = .75$ per unit

Capacitor mva $.75 \times .9 \times 100 = 67.5$ mva.

<u>Case 6 Capacitors switched from wye to delta:</u>

50 mva Y bank

Connected Δ at V_t = .9 per unit

$i_c' = 1.732^2 \times .9 = 2.7$ p.u. current

(Commercial capacitors can withstand 2 times normal voltage for 10,000 cycles.)

<u>Case 7 Series-capacitor compensation for x_d':</u>

50 mva, $x_d' = .4$, $x_c = .5 \times x_d' = .2$ per unit

$E_d' = 1.0 + 1 \times .4 = 1.4$ per unit

$$i_d' = \frac{E_d' - V_t}{x_d' - x_c} = \frac{1.4 - .9}{.4 - .2} = 2.5 \text{ per unit current.}$$

Obviously, methods 1 or 2 have the least to offer and are very unattractive financially. One school of thought on the ratio of capacitors to condenser kvar recommends operation of condensers only partially loaded during off-peak hours and use of spare capacity for peak periods. Yet, the calculations above demonstrate how this lowers the internal voltage and consequently, greatly diminishes the regulation capabilities of the machine, as well as its contribution to stability during fault conditions. The machine losses do not proportionally diminish for this type of operation. The low reactance machine is an improvement over the normal 40% transient reactance machine, but the added cost is discouraging.

Which of the remaining methods is the most attractive depends upon many additional considerations to be discussed later. At least, the series-capacitor compensation scheme rates well among those listed, and promises to be an intriguing subject for investigation. Like many investigations new angles are apt to appear---- perhaps, more significant than the original reasons for the investigation.

Chapter VI

Experimental Tests of a Synchronous Condenser Compensated With a Series Capacitor

Compensation for synchronous-condenser reactance appears to be a very effective method for suddenly magnifying the condenser output by several times. The method boasts of a degree of novelty, but actually it is practical and effective. To obtain experimental data regarding the performance of condenser and capacitor in the proposed arrangement, a simple one machine and infinite bus system was simulated in the laboratory. The circuit diagram appears below:

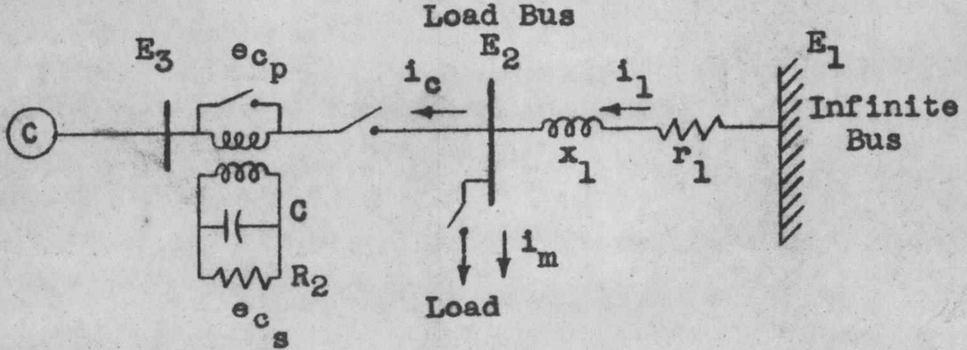


Fig. 15 Experimental Test Circuit

$z_{line} = r_1 + jx_1 = .0374 + j.3524$ per unit

$z_T = .027 + j.024$ p.u.

$x_{d_s} = .76$ p.u.

$x_d' = .221$ p.u.

$x_d'' = .101$ p.u.

$r_e = .036$ p.u.

<u>18.75 kw. = 100% Power</u>

(3 kva Distribution Transformer connected 110/440 volts)

$R_2 = 4.07$ p.u.

It must be emphasized that the machine impedances are much lower than those for conventional synchronous condensers. Consequently, compensation will not have as great effect as for a higher impedance machine. Too, a step-up transformer had to be used to obtain the desired compensation with the capacitors available. This introduced added circuit impedance which had to be subtracted from x_c to obtain the true compensation for x_d'. R_2 appears as a damping resistor to reduce hunting, and oscillations. In addition, the machine's magnetic-circuit time constants and the mechanical inertia are much smaller than for larger machines. This caused difficulty in attempting to switch the compensation into the line during the relatively short transient period of condenser output current; thus, most of the oscillograms show the insertion of compensation after the transient has died out, and it is felt that this demonstrates basic operation just as well, especially since the transient current is small. The proposed sequence of operation consists of the following:

1. A fault condition depresses terminal voltage 10% or more.
2. A voltage element activates the time-delay relay, which trips the capacitor shorting breaker after

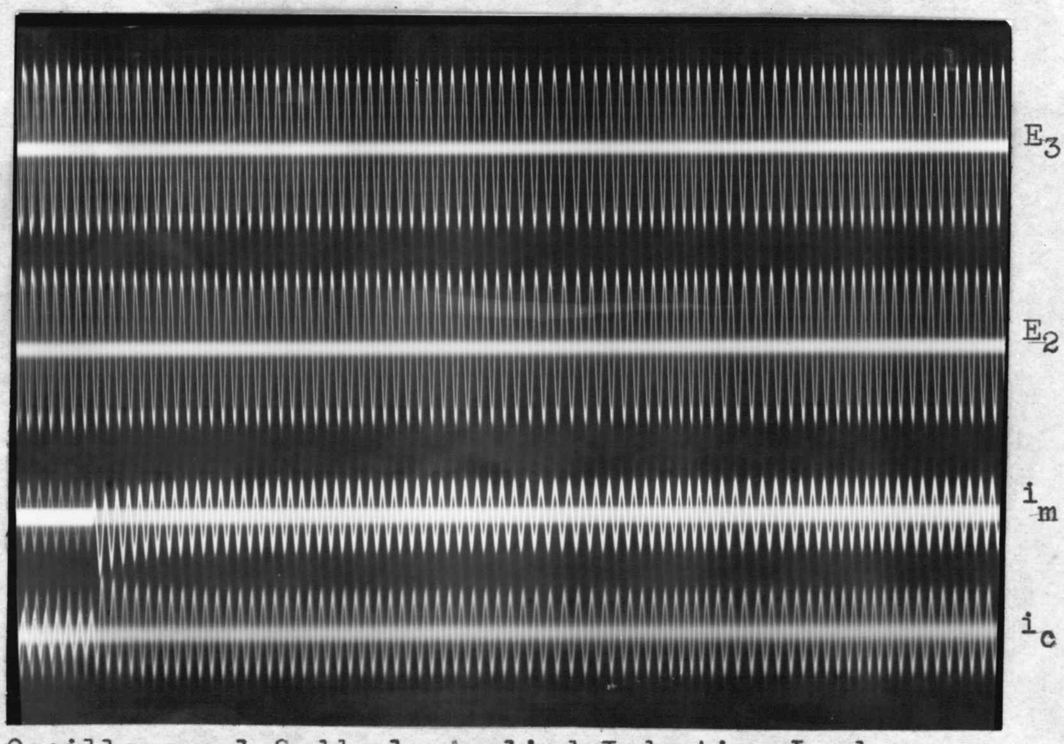
the fault is cleared and blocks tripping for voltages below which recovery is impossible or below which overload on the capacitor and condenser occur.

3. The shorting breaker recloses after an interval of, say, 3 to 5 seconds, or after voltage recovery.

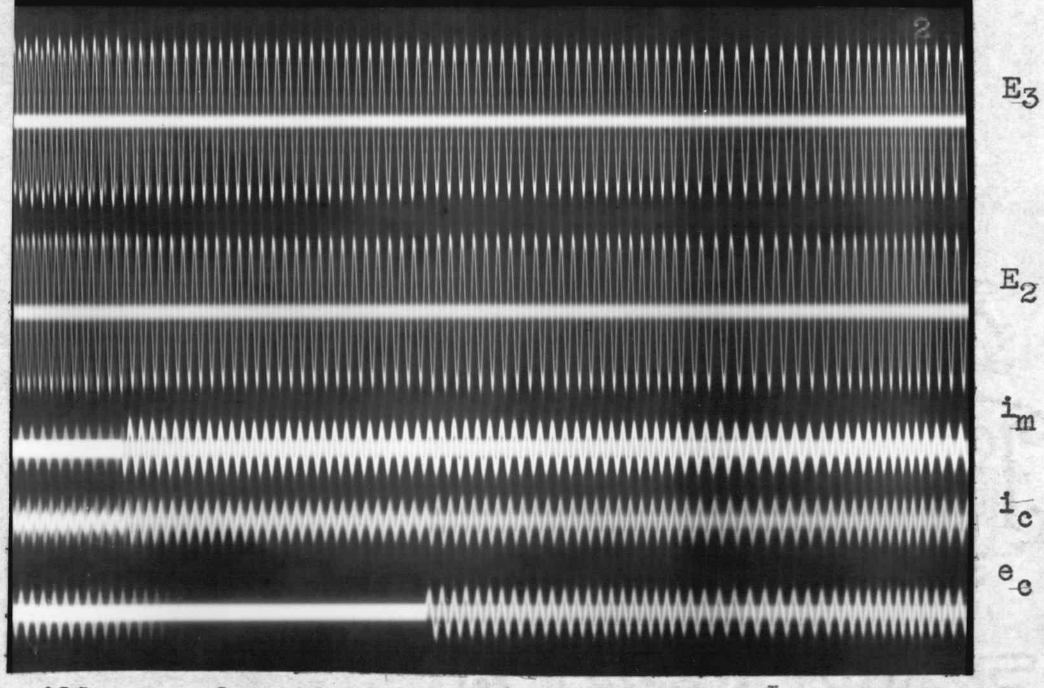
The first test approached this operation by,

1. Depressing the condenser terminal voltage by suddenly switching on a shunt inductive load.
2. Opening the capacitor shorting breaker rapidly after the initial voltage depression.

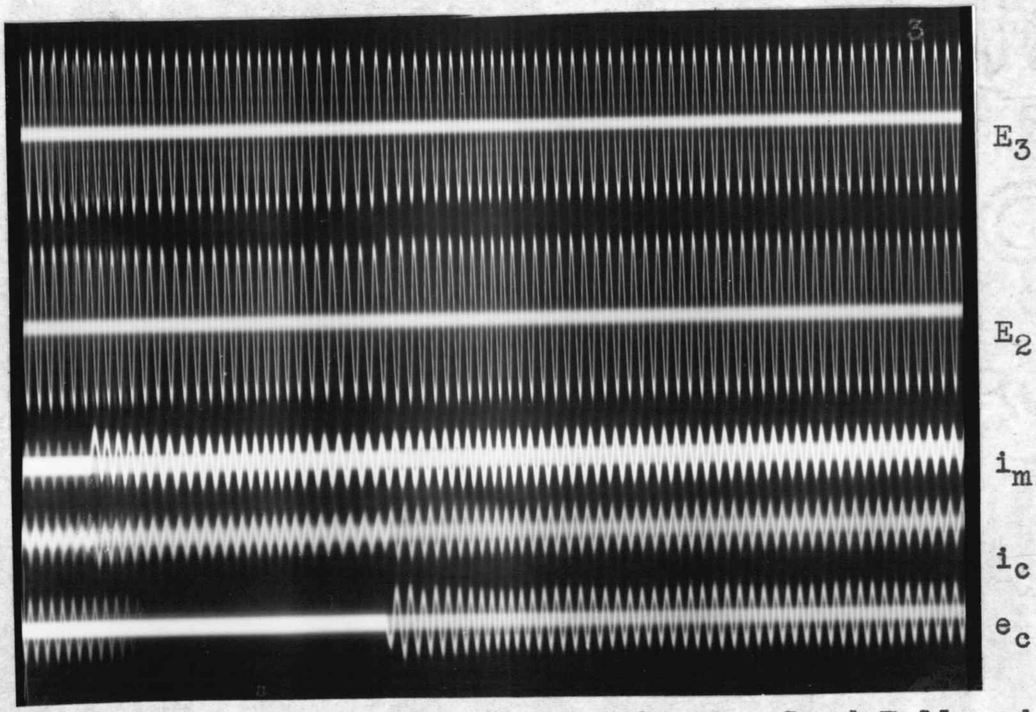
The oscillograms taken show the original steady-state condition with no shunt load, the application of load and resulting voltage depression of E_2, and finally, the insertion of compensation which elevated E_2 and lowered E_3. The series-capacitor voltage is proportional to the condenser current. Actually the capacitor was switched in a little late and should have entered the circuit only several cycles after the initial voltage depression, if the compensation was to be effective during the transient current wave, as it would be on a real system where the transient time constants are of the order of several seconds. The belated insertion of the capacitor only reduced the internal voltage and magnitude of current from the condenser after compensation. The following



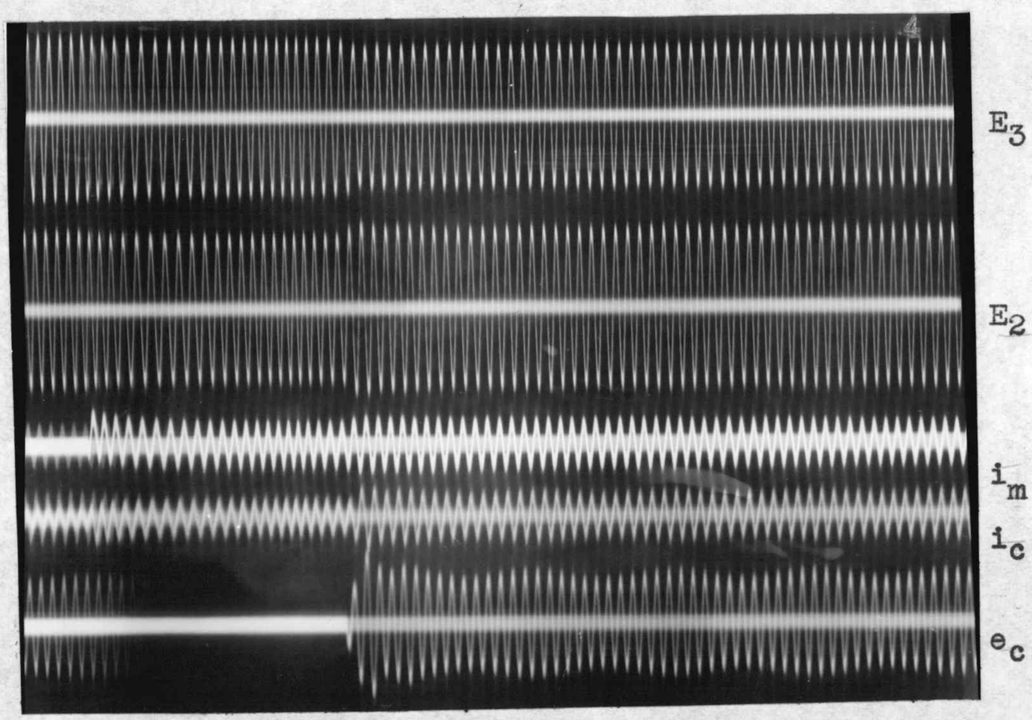
Oscillogram 1 Suddenly Applied Inductive Load
0% Compensation R_2 = 200 Ohms
(Refer to Fig. 15, page 56.)



Oscillogram 2 Suddenly Applied Inductive Load Followed
By Series Capacitor Insertion
66.5% Compensation R_2 = 200 Ohms



Oscillogram 3 Suddenly Applied Inductive Load Followed By Series Capacitor Insertion
76.4% Compensation R_2 = 200 Ohms



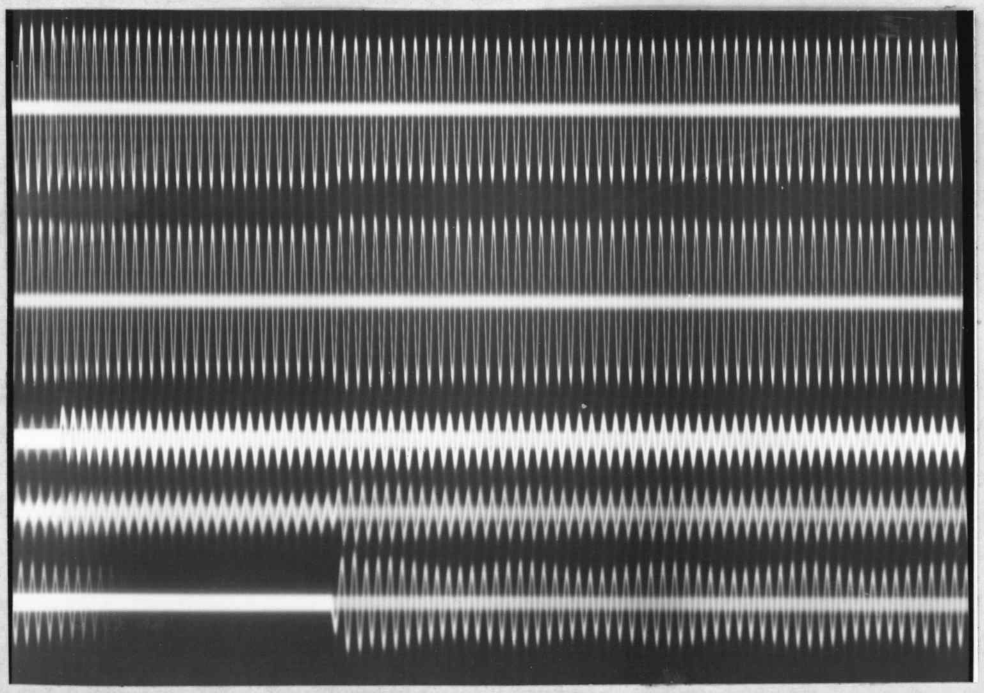
Oscillogram 4 Suddenly Applied Inductive Load Followed By Series Capacitor Insertion
90.8% Compensation R_2 = Ohms

Table 2

Data For Oscillograms 1-5

(Refer To Fig. 15, Page 56, For Legend)

		Volts					Amperes				
Oscillogram No.	Compensation %	E_1	E_2	E_3	e_{c_p}	e_{c_s}	i_1	i_c	i_m	I_f	Time
1.	0	268.5	285.5	285.5	0	0	11.15	11.05	0	4.7	Before Load
	0	261.5	266.0	267.0	0	0	5.5	21.65	17.5	4.7	After Load
2.	0	267.5	285.0	285.0	0	0	11.45	11.3	0	4.7	Before Load
	66.5	261.8	277.5	257.0	12.2	53	8.35	26.2	18.2	4.7	After Load
3.	0	268.5	285.5	285.5	0	0	11.1	11.05	0	4.7	Before Load
	76.4	264.0	286.0	252.0	18.4	77.8	9.6	25.6	18.6	4.7	After Load
4.	0	268.2	285.0	285.0	0	0	11.2	11.05	0	4.7	Before Load
	90.8	264.5	294.0	246.0	24.55	104.7	11.6	30.5	19.1	4.7	After Load
5.	0	267.5	285.0	285.0	0	0	11.2	11.05	0	4.7	Before Load
	90.8	262.5	292.5	245.0	24.8	103.6	11.3	30.1	18.85	4.7	After Load



Oscillogram 5 Suddenly Applied Inductive Load Followed By Series Capacitor Insertion 90.8% Compensation $R_2 = 200$ Ohms (Refer to Fig. 15, page 56.)

figures are the oscillograms and data for 0, 66.5, 76.4, and 90.8 per cent compensation for x_d', respectively. For these oscillograms a high internal voltage was maintained at the value corresponding to rated field current and considerably less than normal current. Higher than normal terminal voltages had to be used to reduce the condenser current. Otherwise, the series-capacitor voltage rating would have been exceeded. The infinite bus voltage remained constant within 2.6%. The plot below describes the general variation of condenser

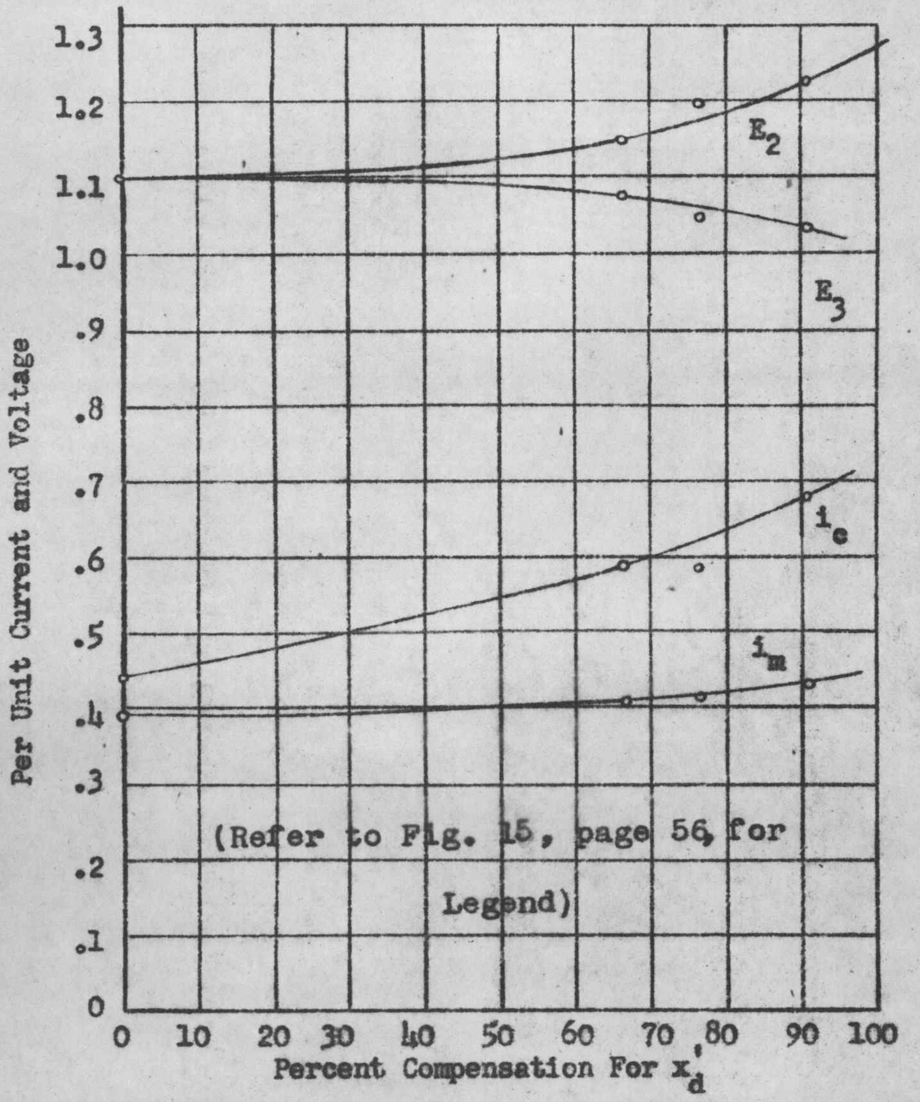


Fig 16 Results of Oscillograms Showing Steady-State Current and Voltages For Constant Load and Constant Sending-End Voltage

terminal voltage, condenser bus voltage, load current, and condenser current for varying degrees of compensation. It merely illustrates how much the compensation can improve the receiving-end voltage of a transmission line with no other ties.

The portion of the oscillograms just after insertion of the capacitor displays little transient effect because of the small resultant voltage, $E_d' - E_t$, and a masking of detail by the small amplitude used on the oscillogram. Increased compensation clearly produces a larger current, and almost instantaneously, within a cycle or two of the insertion time, elevates the bus voltage to its new steady-state value. If the insertion had occured during decay of the condenser current, then the voltage elevation and condenser current would have been still greater, but they would eventually decay to the steady-state value already shown on each oscillogram. Furthermore, the rapid rise of load bus voltage with condenser current has greatly subdued the current one would expect from calculations using the initial depressed voltage, occasioned by suddenly switching on the inductive load before the capacitor is introduced. This effect was mentioned previously on the large system with inter-ties. In this single machine problem line regulation portrays an important role, and any calculation of condenser current following compensation must unavoidably include line impedance. Consider the case of 90.8% compensation and $R_2 = 0$:

Before load is switched on:

$E_1 = 268.2v = 1.119$ p.u.

$E_2 = 285\ v = 1.188$ p.u.

$i_c = 11.05$ amp $= .246$ p.u.

$x_d' = .221, \quad r_e = .036$ p.u.

Neglecting resistance drop,

$E_d' = E_2 + i_c\, x_d'$

$E_d' = 1.199 + .246 \times .221 = 1.242$ p.u.

The maximum value of transient condenser current upon depression of terminal voltage by the load is given by

$i_d' = \dfrac{E_d' - V_t'}{r_e + jx_d'}$. V_t' is measured form the oscillogram as 1.110 p.u. (Instantaneous voltage after the load is applied.)

$$i_d' = \frac{1.242 - 1.110}{.036 + j.221} = .590 \text{ p.u.}$$

<u>After insertion of compensation:</u>

$C = 240$ Mfd., $-jx_c = \dfrac{1}{16} \times \dfrac{10^6}{377 \times 240} = \dfrac{1}{3.075} = .225$ pu

$z_T = .027 + j.024$ p.u.

$V_t' =$ Terminal voltage just before compensation

$= 1.093$ p.u. (measured)

$E_{d_o}' =$ internal voltage just before compensation

$= 1.093 + .532 \times .221 = 1.211$ p.u.

$i_{d_o}' =$ steady-state condenser current achieved just before insertion $= .532$ p.u. (measured)

If the condenser terminal voltage remained depressed after compensation the maximum condenser transient current, neglecting subtransient effects, would have been, $i_d' = \dfrac{E_d' - V_{t_o}'}{r_e + r_t + j(x_d' + x_t - x_c)} = \dfrac{.532 \times .221}{.063 + j.020}$

$= 1.79$ per unit

Actually the bus voltage did not remain depressed because the increase in condenser current immediately brought up the bus voltage, E_2. As measured the maximum value of i_d' after insertion was .689 per unit.

A more precise solution for i_d' can be made. Noting from the oscillogram that the load current remains essentially constant and lags E_2 by 90^o, the circuit reduces to the following equivalent:

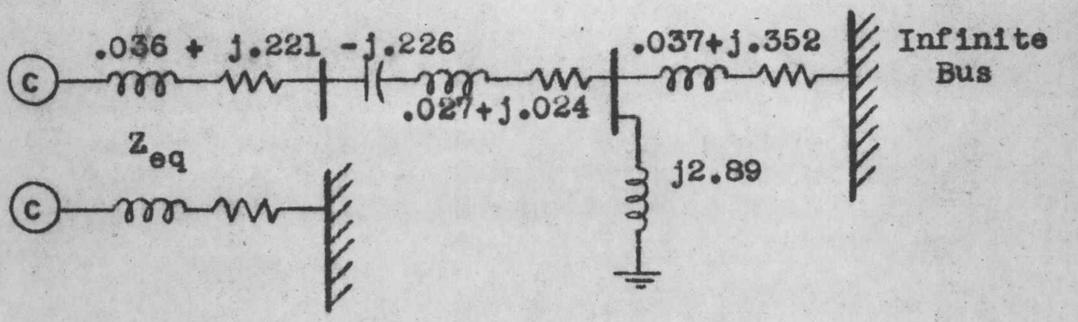


Fig. Equivalent Test Circuit Representation

<u>By Thevenin's Theorem:</u>

$$Z_{eq} = \frac{(j2.89)(.036+j.221-j.226+.027+j.024)}{.036+.027+j(.221-.226+.024+2.89)} + .037+j.352$$

$Z_{eq} = .099 + j.373$ per unit

Since i_c in the readings can be obtained as the algebraic difference, $i_1 - i_m$, i_c and i_m are nearly opposite in direction. I_m lags E_2 by 90^o; therefore, i_c leads E_2 by 90^o approximately. I_1 and the line impedance are nearly all reactive, making E_1 and E_2 in phase. Hence, i_c leads E_1 by nearly 90^o.

<u>After capacitor insertion:</u>

$E_1 - i_1'(.099 + j.373) = E_{d_o}'$

$1.104 \angle 0^o - ji_1'(.099 + j.373) = 1.211 \angle 0^o$

$(1.104 + .373\, i_1')^2 + (.099\, i_1')^2 = 1.211^2$

$$i_1' = .286 \text{ per unit}$$

$i_d' = i_1' + i_m' = .286 + \frac{19.1}{45} = .710$ p.u. $= 31.97$ amps.

This agrees reasonably well with the observed maximum transient condenser current after compensation, $i_d' = 31$ amperes.

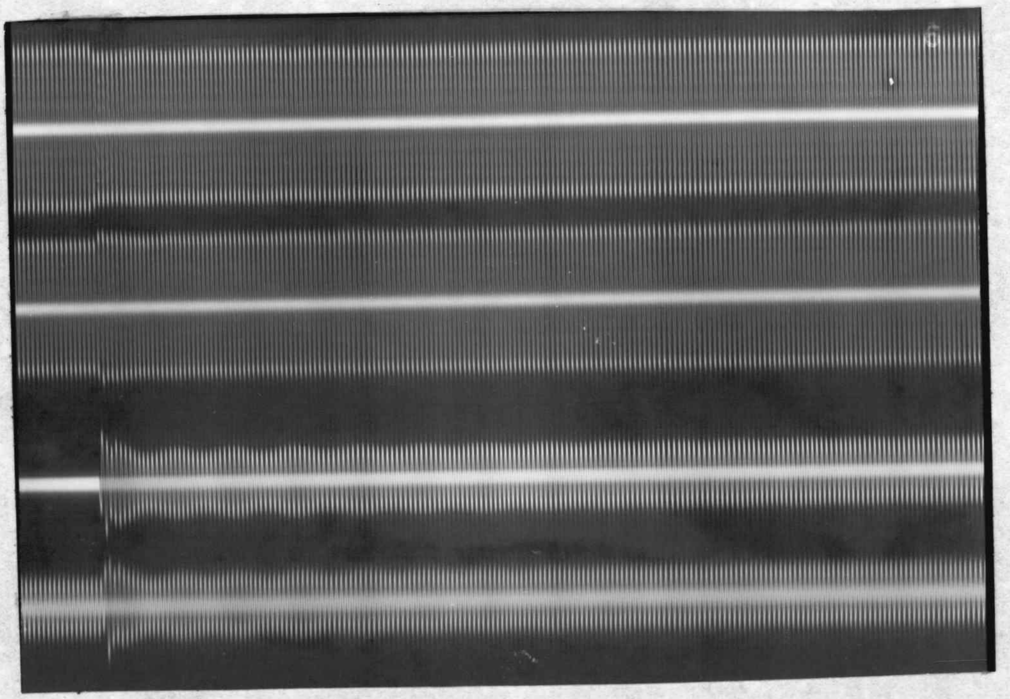
The foregoing calculations suggest that the increment of condenser current engendered by compensation depends to a large extent upon:

1. The initial condenser internal voltage behind transient reactance, as set by excitation and the original terminal voltage before the fault.
2. The amount of initial voltage depression.
3. The degree of compensation.
4. The driving point impedance of the system as viewed from the condenser bus. Actually a small subtransient component of current appears when the capacitor enters the circuit, but its duration is too short to warrant consideration in this application

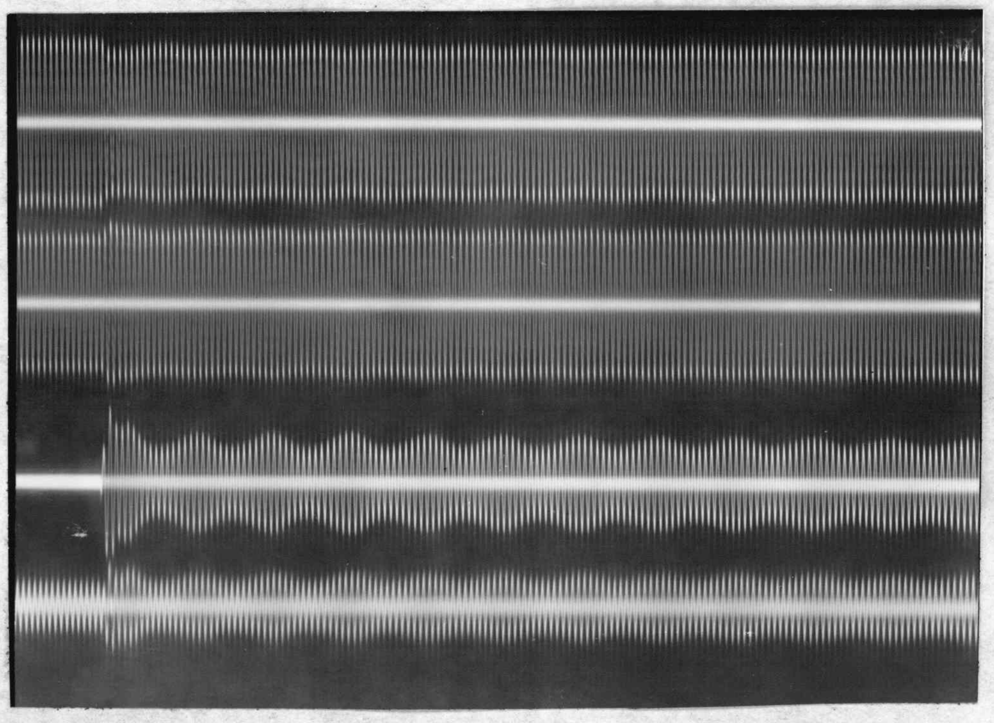
to stability.

Evidently, a high driving point impedance restricts the condenser current severely, but only a small increase in condenser current is necessary in such a case to bring the load bus voltage up again. Compensation on a system with low driving point impedance, as at points of inter-tie on large power systems, will create higher condenser currents because the load bus voltage will not be so susceptible to change with the output of the synchronous condenser.

Many oscillograms were taken of different conditions. In general, too much compensation, low excitation, low terminal voltage, or any combination of these easily led to instability of the synchronous condenser or hunting conditions. Of course, the small low-inertial machine is more prone to hunt than the 50 mva condenser, but both machines comply with the same physical laws governing hunting. Like the larger machines this test machine had a damper or amortisseur winding which normally suppresses hunting in larger machines to a good extent. When the terminal voltage varies due to the hunting of the synchronous condenser, the hunting becomes cumulative, and much more serious than in the case where the bus voltage is less dependent upon the condenser output, as in a larger power system. Practically all these oscillograms display some hunting tendencies upon change of external circuit constants, whether the machine is compensated or not. Note the sinusoidally varying character of the envelope of the condenser-current wave in each case. In oscillograms 6 and 7 two cases are shown when the capacitor was inserted into the circuit with only the condenser and line impedance attached to the infinite bus. The case with 83% compensation was decidedly less stable than the 66.5 case, although the machine recovered itself each time. The circuit was not loaded in these two cases except by the condenser. Refer to Fig. 15, page 56.



Oscillogram 6 Sudden Insertion Of Series Capacitor
66.5% Compensation R_2 = 177 Ohms
(Refer to Fig. 15, page 56.)



Oscillogram 7 Sudden Insertion of Series Capacitor
83.0% Compensation R_2 = 177 Ohms
(Refer to Fig. 15, page 56.)

In the following set of oscillograms the series capacitor was already in the circuit and an induction motor was suddenly started at the receiving-end of the line. These oscillograms also convey an interesting picture of the relationship between compensation and the degree of hunting. The same excitation and condenser terminal voltage were adjusted for initially, while the amount of compensation varied for each case. Without compensation, oscillogram 8, the condenser was very stable for suddenly applied load. When the load

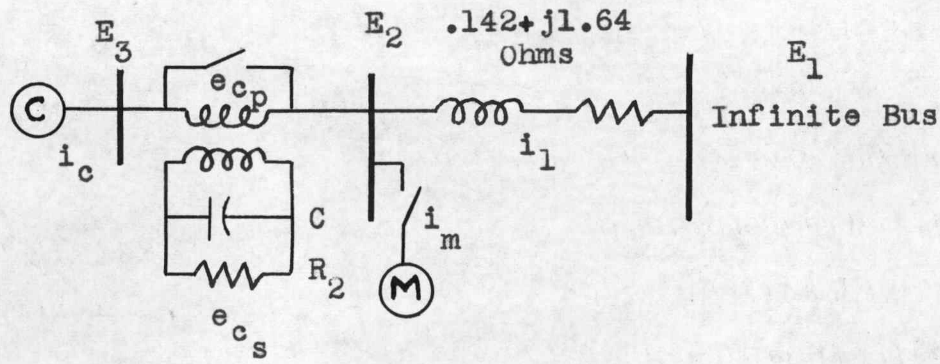
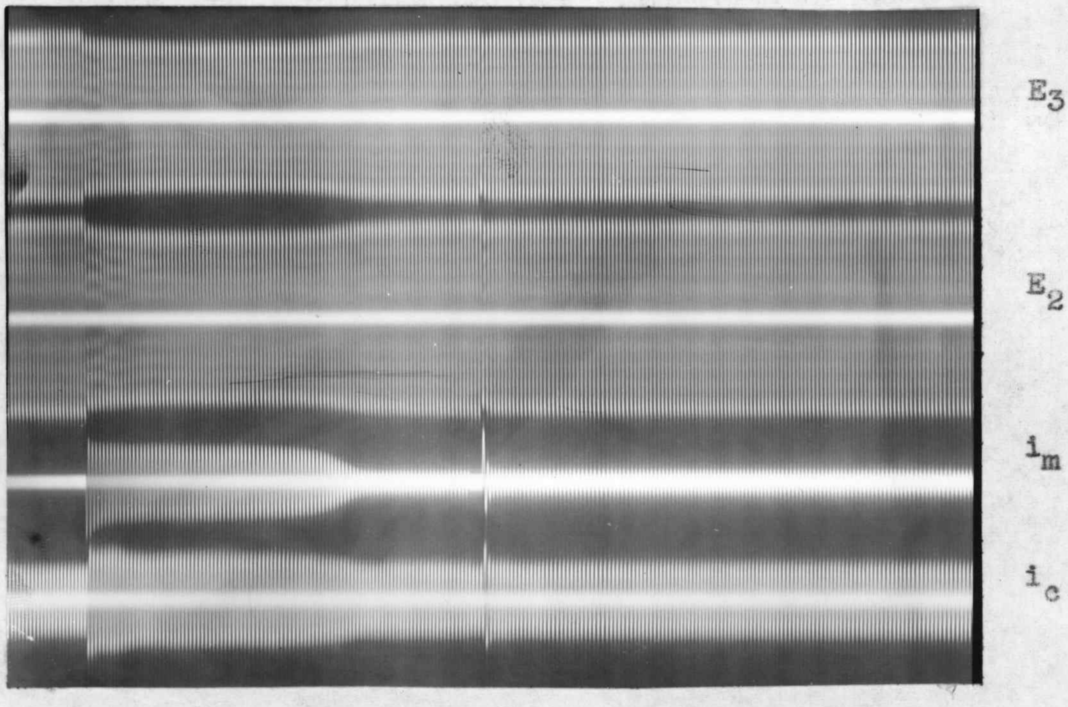


Fig. 18 Test Circuit For Oscillograms 8 - 10.



Oscillogram 8 Sudden Starting of Induction Motor
0% Compensation R_2 = 177 Ohms
(Refer to Fig. 18, page 71.)

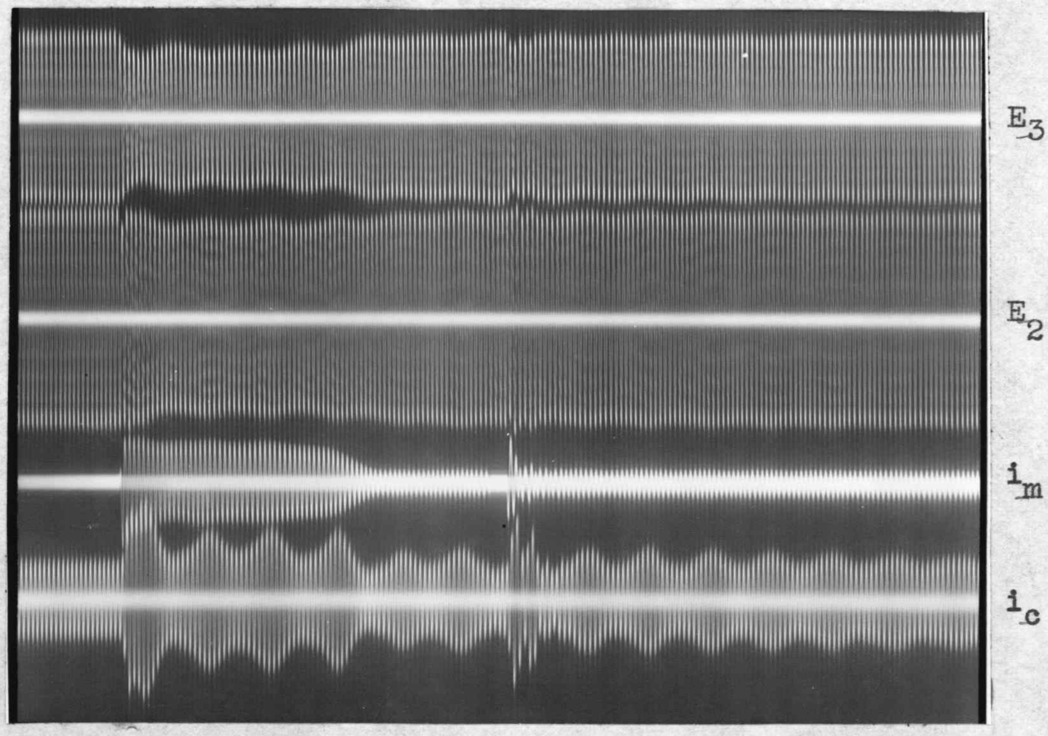
instantaneously depressed the terminal voltage we observe the condenser responded immediately. This is the valuable inherent regulation characteristic of the synchronous condenser in action, which involves no time delay since

Table 3

Data For Oscillograms 6 - 10

Volts (Refer To Fig. 15, Page 56) Amperes

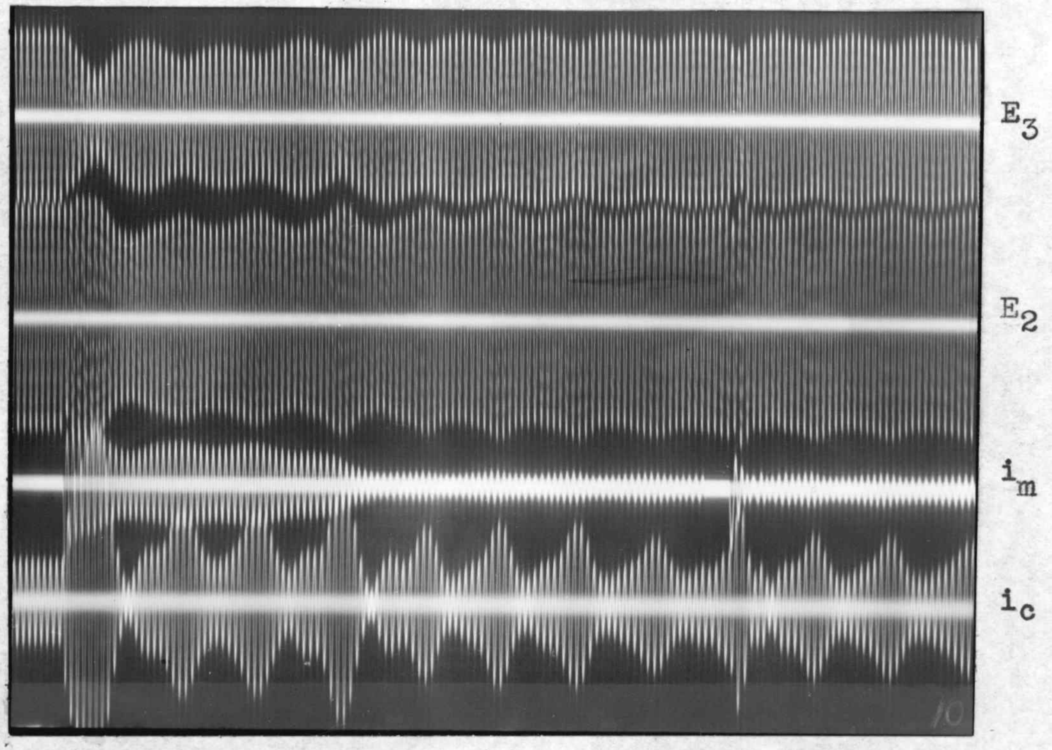
Oscillogram No.	% Compensation	E_1	E_2	E_3	e_{c_p}	e_{c_s}	i_1	i_m	i_c	I_f	Time
6.	213.7	213.7	243.0	240.0	0	0	32.3	0	32.3	4.7	Before Load
	66.5	223.0	257.4	223.0	18.37	79.7	39.8	0	39.8	4.7	After Load
7.	0	214.2	243.0	240.0	0	0	31.9	0	31.9	4.7	Before Load
	83.0	227.0	262.3	218.6	23.6	102.0	41.9	0	41.9	4.7	After Load
8.	0	214.2	243.0	240.0	0	0	32.5	0	32.5	4.7	Before Load
	0	210.0	236.0	233.5	0	0	29.9	5.5	35.0	4.7	After Load
9.	66.5	240.0	269.0	240.0	14.9	65.0	32.3	0	32.1	4.7	Before Load
	66.5	236.0	261.8	230.0	16.6	74.0	27.7	7.0	36.3	4.7	After Load
10.	83.0	246.3	274.2	240.0	18.1	77.9	31.9	0	31.8	4.7	Before Load
	83.0	242.0	267.8	229.9	20.9	90.0	29.3	7.5	36.2	4.7	After Load



Oscillogram 9 Sudden Starting of An Induction Motor
66.5% Compensation $R_2 = 177$ Ohms

the condenser current must satisfy the equation,

$i_d' = \dfrac{E_d' - V_t'}{x_d'}$, at the instant E_t changes. E_d', the voltage behind transient reactance, cannot change immediately because the armature flux-linkages cannot change suddenly, as stated in the theorem of constant flux linkages. Actually a small sub-transient component of current occurs during the first several cycles, but the short duration produces negligible effect on stability and deserves consideration only from the standpoint of momentary aid



Oscillogram 10 Sudden Starting of An Induction Motor
83% Compensation $R_2 = 177$ Ohms
(Refer to Fig. 18, page 71.)

to voltages. The usual exponential decay of current is barely detectable because of the poor regulation of E_2, which tempers the magnitude of i_d'.

Unfortunately, sufficient capacitors were not available to determine what amount of compensation would just start hunting. The tendency to hunt depends upon the inertia, terminal voltage, excitation, and reactance of the machine. The hunting is the result of shock to the machine when the terminal voltage is suddenly depressed.

The power or displacement angle of the rotor must change slightly for the new terminal voltage condition and the re-distribution of flux in the air-gap, Since the compensation effects the depression of V_t, the amount of compensation directly influences the tendency to hunt. This is very apparent in the oscillograms above, where 83% compensation produced a very strong propensity to hunt. Had the bus voltage, E_2, fluctuated less after application of the load, then the rocking rotor would have been more rapidly subdued. There is no doubt concerning the amplification of condenser current by this means, but the hunting problem poses a series limitation, even at lower values of compensation below 50%. However, the inertia of larger machines will permit them to ride through disturbances, such as these, with relative ease.

If large synchronous condensers can maintain stability on 10 to 20% normal voltage, then let this be the criteria for the maximum permissible value of compensation for stability. For a 40% transient reactance machine carrying 1 per unit originally, the maximum compensation by this criteria can be computed as a function of minimum bus voltage:

$V_t = 1.0$ p.u. original steady-state terminal voltage

$E_d' = 1.0 + .4 \times 1.0 = 1.4$ p.u.

(Maximum permissible) $i_d' = \dfrac{1.4 - .1}{.4} = 3.25$ p.u.

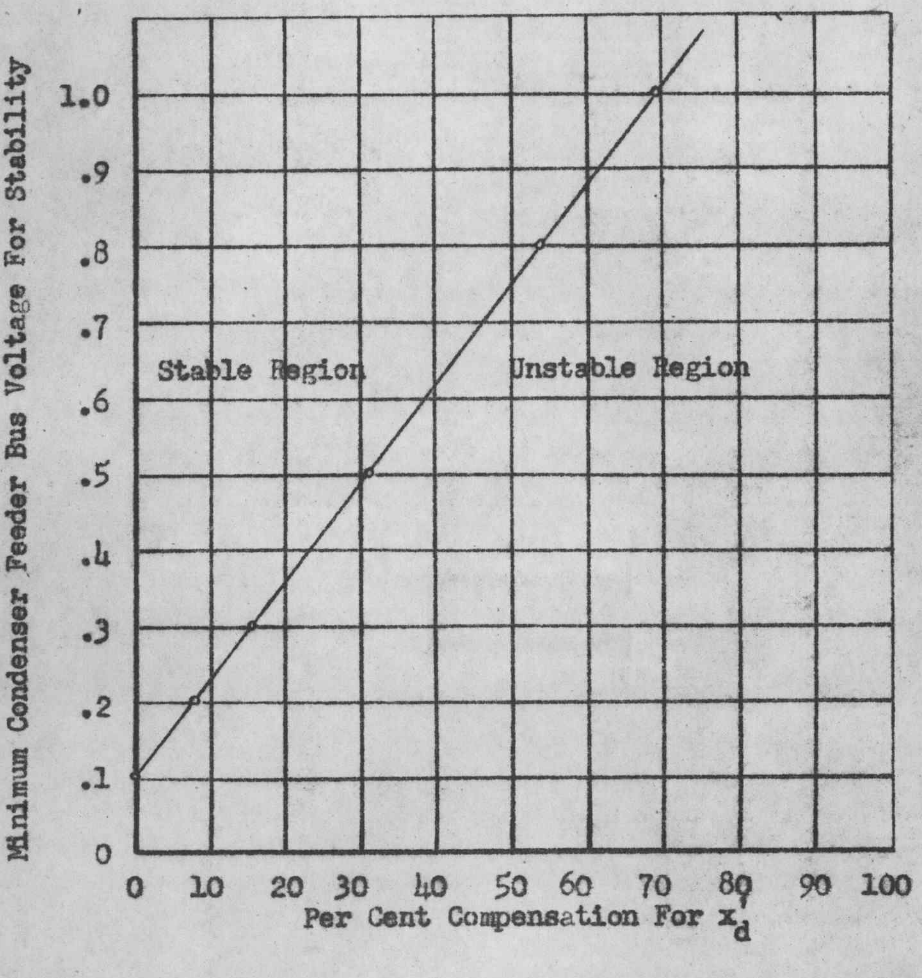


Fig. 19 Stability Chart For a Compensated Condenser, x'_d = 40%. Minimum Condenser Terminal Voltage For Stability Assumed 10%.

Let .3 p.u. be the minimum bus voltage for which we wish to maintain stability; then the maximum permissible compensation is,

$$x_c = \frac{E\ \text{bus} - V_t'}{i_d'} = \frac{.3 - .1}{3.25} = .0616\ \text{p.u.} = \frac{.0616}{.400} \times 100$$

x_c = 15.4% Compensation

As a further illustration suppose system voltages were such that the condenser bus voltage could not decrease to lower than .5 p.u. voltage except for a bus fault, in which case instability would ensue regardless. Then we could tolerate 30.8% compensation:

$$x_c = \frac{.5 - .1}{3.25} = .123\ \text{p.u.} = \frac{.123}{.400} \times 100 = 30.8\%\ \text{compensation.}$$

The curve in Fig. 9 was computed similarly. Past experience with the experimental machine has shown that stability exists until about 40% terminal voltage. In oscillogram 10 with 83% compensation, the terminal voltage shrank to .595 per unit on the first big dip, and the machine barely remained in step. If the load bus voltage had been much lower, instead of rising as it did, then the condenser would surely have lost synchronism.

For large currents during compensation emphasis must be placed upon a high internal voltage in the machine. By this reasoning one might recommend a fairly high reactance machine to obtain the high internal and then compensate higher than would be required for the low reactance machine. However, the fallacy of this reasoning becomes apparent in a simple calculation. For example, let the initial condition be $V_t = 1.0$ p.u. and the transient condition be $V_t' = .5$ p.u.

$\underline{x_d' = .3 \text{ p.u.}:}$ $\qquad E_d' = 1.0 + 1.0 \times .3 = 1.3$ p.u.

Maximum compensation allowing 10% minimum terminal voltage: $i_d'\ (\text{max.}) = \dfrac{1.3 - .10}{.3} = \dfrac{1.2}{.3} = 4.0$ p.u.

$$x_c = \frac{.5 - .1}{4.0} = .10 \text{ p.u.} = 33.3\% \text{ compensation}$$

$$i_d' = \frac{1.3 - .5}{.3 - .1} = 4.0 \text{ p.u.}$$

$\underline{x_d' = .6 \text{ p.u.}:}$ $\qquad E_d' = 1.0 + 1.0 \times .6 = 1.6$ p.u.

Without compensation the above case ($x_d' = 0.3$ p.u.) gives $i_d' = 2.67$ p.u., and with $x_d' = .6$, $i_d' = \dfrac{1.6 - .5}{.6} = \dfrac{1.1}{.6} = 1.833$ p.u. (Note how much smaller i_d' is in this case if no compensation is used.)

Maximum compensation allowing 10% minimum terminal voltage:

$$i_d'\ (\text{max.}) = \frac{1.6 - .1}{.6} = 2.5 \text{ p.u.}$$

$$x_c = \frac{.5 - .1}{2.5} = .16 \text{ p.u.} = 26.6\% \text{ compensation}$$

The 60% machine can produce only 2.5 p.u. current with stability on 50% bus voltage while the lower reactance machine of $x_d' = 30\%$ can withstand 4.0 p.u. and yet maintain stability. Evidently, the gain in internal voltage derived by increasing the machine's reactance is all lost because the voltage has to work through a higher impedance and yet preserve 10% voltage at the terminals of the machine. The function for maximum permissible current for stability, $i'_d = \frac{(1.0 - x'_d) - .1}{x_d} = 1.0 - \frac{.9}{x_d}$, obviously, decreases as x'_d increases. Hence, our only recourse for large output is to employ low reactance machines and maintain a high internal voltage by keeping the machine well loaded.

What happens if the condenser is drawing lagging current or is under-excited when compensation is introduced? In this case,

$$i'_d = \frac{0.9 - 1.0}{j\,(x'_d - x_c)}$$

$$= \frac{-.1}{x_d - x_c},$$

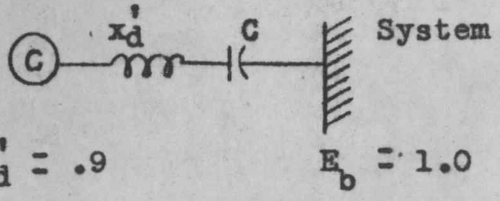


Fig. 20 Equivalent Circuit For Compensated Condenser When Drawing Lagging Current

and the amount of lagging current only increases. Clearly, relaying must guard against such operation when the condenser is used to aid stability.

Pre-suppose that the condenser normally operates at zero output and is used only to correct for large voltage fluctuations. Then, the capacitor is inserted on a voltage rise or depression or —what is better— remains in continuous operation. As a matter of fact, at zero output the presence or absence of the capacitor does not affect the condenser output. When E_b decreases suddenly, the current becomes strongly leading, and when the voltage suddenly jumps, the current becomes strongly lagging. Both currents are in such a direction as to oppose voltage changes. The machine merely appears to have a lower reactance.

So far we have limited the amount of compensation for x_d' to considerably less than 100 percent. It was observed in previous data and is recognized that some system impedance is present and invalidated the assumptions of a true infinite bus at the condenser substation, even at the 230 kv bus. Likely the 5 to 10% system impedance will allow the series-capacitor reactance to increase a like amount above what has been used in previous calculations. In addition, it should be pointed out that compensation above 100% would also result in greater than 10% condenser terminal voltage. Let $V_b = 1.0$, $i_{ss} = 1.0$, $V_b' = .5$ p.u., and $x_d' = 40\%$. A plot of condenser terminal voltage and current is shown in Fig. 21 for varying compensation. It is clear that the machine terminal voltage is greater than .1 p.u. for any value of compensation outside the range 28-38%. From 0 to 28% the machine is stable and performs correctly. From 28 to 38% compensation the machine is unstable.

$$i_d' = \frac{1.4 - .5}{.4 - .4 \times \%Comp./100} = \frac{.9}{.4(1 - \%Comp./100)}$$

$$E_t' = 1.4 - \frac{.9}{1 - \%Comp./100}$$

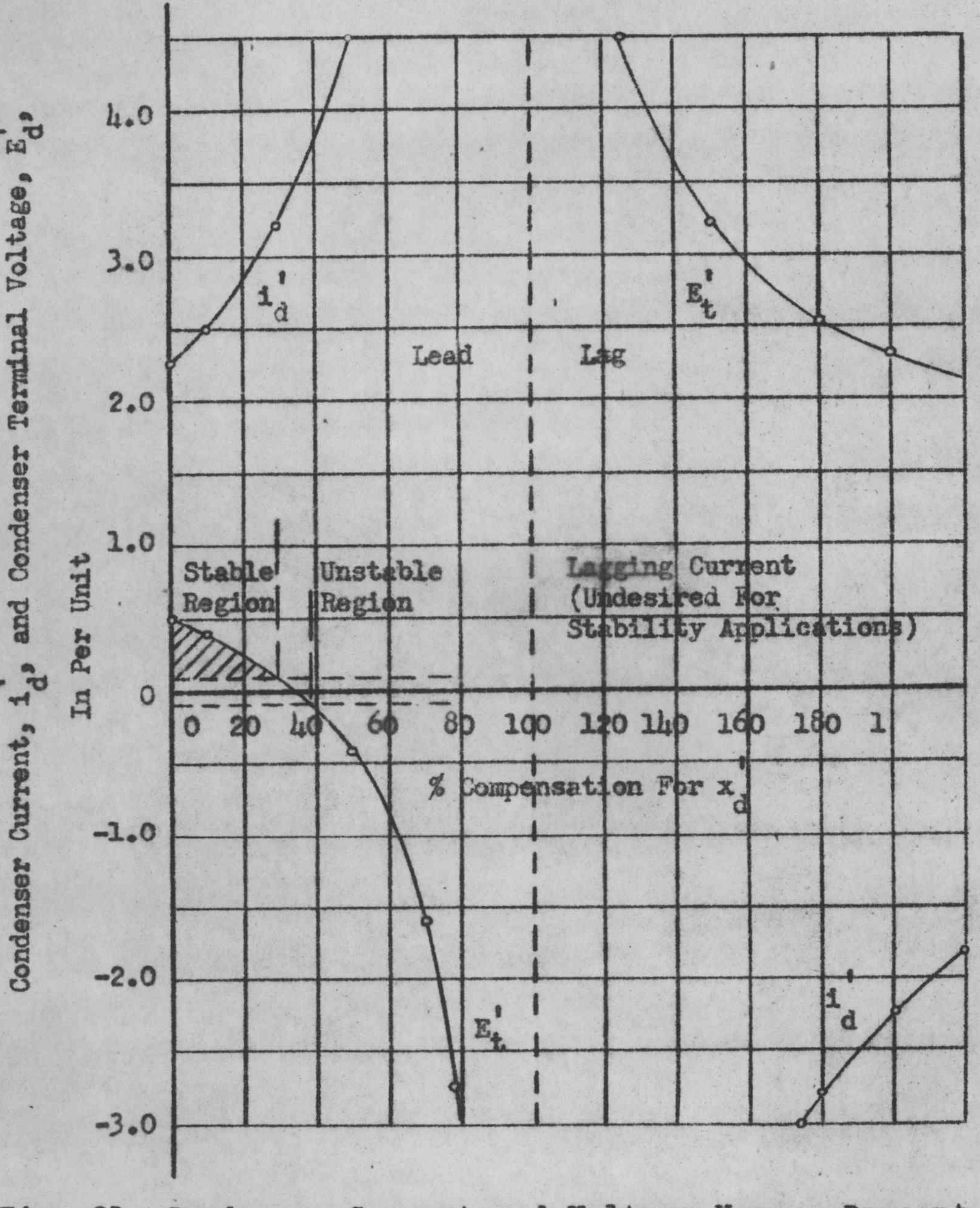


Fig. 21 Condenser Current and Voltage Versus Percent Compensation For a 30 Mva, 40% x_d' Condenser, Assuming a Constant Bus Voltage of .5 Per Unit.

From 38 to 100% the machine is unstable, and current and voltage ratings of the normal synchronous condenser and series capacitor are being strained and exceeded. Furthermore, if the bus voltage goes below or above the assumed value of .5 for this graph, the condition is entirely changed. Below .5 p.u. voltage the stable hatched area would diminish; above .5 it would increase (see Fig. 19). Beyond 100% compensation the condenser draws lagging current, which would not be desirable. In view of these aspects Fig. 18 appears to be the best source for the amount of compensation to use in the practical case. If we wish to include the effects of system impedance in these curves, then assume that the system impedance has already been subtracted from the reactance of the series capacitor in determining the percent compensation for x_d'.

One other physical problem arouses a tone of perplexity. All calculations treat the series capacitor as compensation for the transient reactance. Yet, we know that compensation will increase both sub-transient and steady-state components of current. For stability purposes the sub-transient is too short to affect either the stability of the machine or the system. It is important only in the correction for fluctuating voltages. In the steady-state, condenser output is governed by saturated synchronous reactance, which is much larger than the transient reactance. Since the major system swings and the tendency for the condenser and system to lose synchronism will all climax before the end of the first second after the fault, the steady-state reactance of the machine is of little concern to machine stability and the tolerable amount of compensation.

Apparently, series-capacitor compensation for synchronous condenser reactance can multiply normal condenser current several times and without any hesitation. There are, however, restrictions to the amount of compensation practicable, of which stability is one. For a normal 40% transient reactance machine the plot of Fig. 19 shows that even 31% compensation would make the machine unstable if the bus voltage dropped below .5 per unit. It is not unusual that severe faults on a large system drive some voltages near the fault or even away from the fault to values below .5 p.u. and yet, do not promote instability. For this reason either low compensation or a protective relay must block the compensation on very low voltage conditions. Usually voltages return to well above .5 p.u. once the fault is cleared, and so, careful coordination with breaker operating times will conceiveably allow compensation to about 50 percent with such a condenser.

Chapter VII

Continuous Compensation For Flickering Voltages

Erratic loads such as arc furnaces, electric welders, motors supplying intermittent loads like power saws, and the starting of electric motors frequently incite a troublesome flickering voltage condition on power systems. If the system impedance between the vacillating load bus and the internal voltage of generation were zero, there would be zero voltage regulation at that bus, but such is not the practical case. Instead, system impedance more nearly approximates 5 to 10%, so that a change of 1 per unit current will induce a 5 to 10% change in voltage at the load bus. It has been proposed many times that a synchronous condenser be used at the load bus, in effect, to lower the system impedance and so ameliorate the flicker condition. However, the normal 25% subtransient reactance condenser helps but little, since the system impedance would still be $\frac{5 \times 25}{30} = 4.17\%$. Although a very low subtansient reactance would evince considerable improvement the economics are usually unattractive. Conceivably, some installation could utilize a normal condenser with financial justification if the condenser could appear larger or of lower reactance than its actual cost permits. This condition has been approached in practise by placing a reactor in series with the feeder line to the load bus as shown in Fig. 22. By this means load changes reflect a greater voltage change at the condenser terminals and produce a larger corrective current from the condenser.

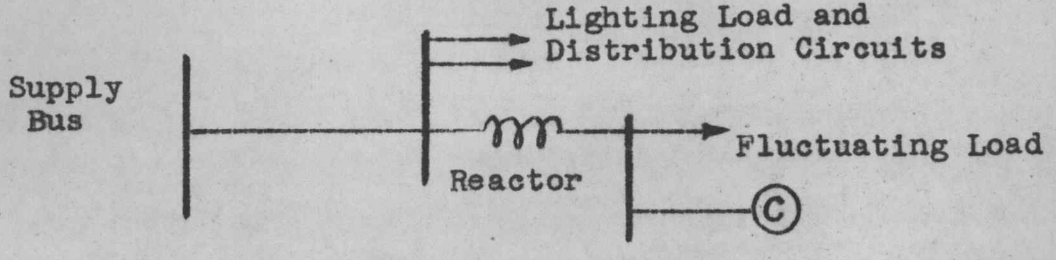


Fig. 22 Reactor Scheme For Correcting Fluctuating Voltage.

An alternative proposal for improving flickering voltage conditions consists of a compensated synchronous condenser. This application of compensation involves continuous compensation which, in effect, avails the flickering load bus of a low impedance condenser at all times. The equivalent machine steady-state reactance as viewed from the load bus becomes lower with increased compensation, which consequently, increases the steepness of the machine's characteristic V curves, as shown in Fig. 23. Thus, a small change in terminal voltage creates a much larger increment of current change for the compensated machine than it does for the uncompensated machine. The compensated condenser proves a much better voltage regulating device than the same machine uncompensated. Likewise in the transient state the apparent lower machine impedance may provide the best solution for flickering

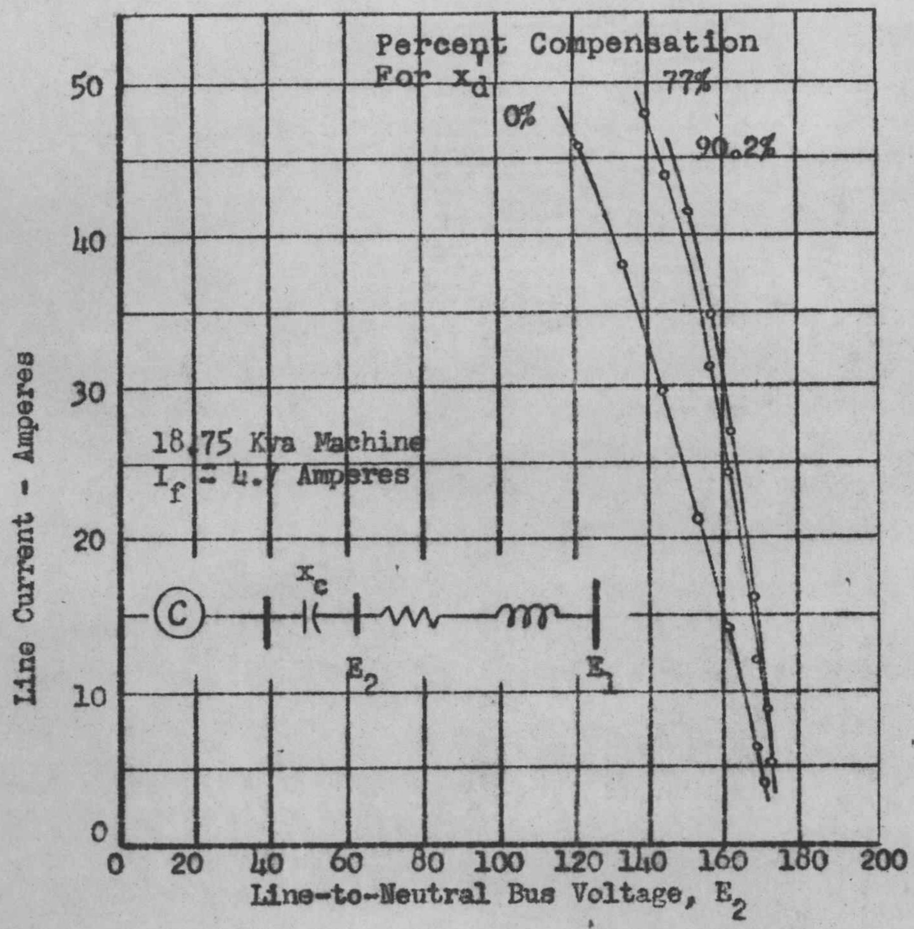


Fig. 23 Effect of Compensation on Synchronous Condenser Steady-State Voltage and Current Relationship.

voltages.

Both the compensated condenser and reactor plan suffer stability infirmities, if employed with too much compensation and reactance, respectively. In addition, the customer load bus still fluctuates in the reactor scheme, which may or may not be an objection, depending on the nature of the load. If the fluctuating load contains no lighting load but only motors, then the reactor behaves like a starter for the starting and load acceptance processes experienced by the motor. Line surges will then be smaller, but motor torques will decrease correspondingly. An example will better illustrate the characteristics of this plan:

Assume the following typical circuit:

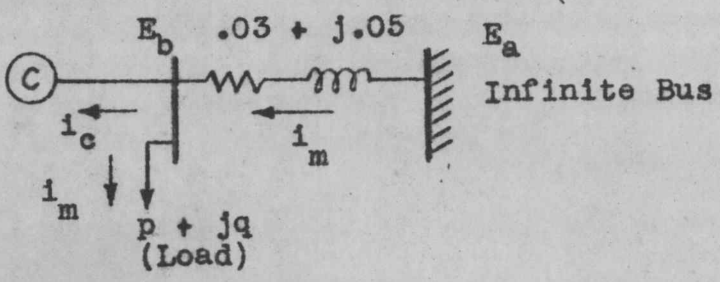


Fig. 24 Normal Condenser Used To Correct For Fluctuating Voltage.

<u>10 Mva Base</u>

5 Mva Condenser; $x_d'' = 25\%$ on own base $= .5$ at 10 mva

$p + jq = 1 - j.5$, $i_m = \dfrac{1 - j.5}{1.0} = 1 - j.5$

$E_b = 1.0 \underline{/\theta^\circ}$, $i_c = \dfrac{j.5}{1.0} = j.5$

Then steady-state operation establishes E_a;

$E_a = E_b + i_1 (.03 + j.05) = 1.03 + j.05 = 1.03$ p.u.

E_d'' = voltage behind subtransient reactance $= 1 + i_c x_d''$

$= 1 + j.5 \times j.5 = 1.25$ p.u.

During a transient condition when i_m suddenly jumps to $4 - j2$, E_b can be determined as follows:

$\bar{E}_a - \bar{E}_b = \bar{Z}_1 (\bar{i}_c + \bar{i}_m)$ $\qquad \bar{E}_a = E_a \underline{/\theta}$

$$(1.03 \sin\theta + j\,1.03 \cos\theta) - E_b \underline{/0} = (.03 + j.05) \times \left[(4 - j2) + j\,\frac{(1.25 - E_b)}{.5}\right]$$

$(1.03 \sin \theta - E_b) + j(1.03 \cos \theta) = (.095 + .10E_b) +$
$j(.215 - .06E_b)$

$1.03 \sin \theta - E_b = .095 + .10E_b$ -------------------- (1)

$1.03 \cos \theta \quad = .215 - .06E_b$ -------------------- (2)

Simultaneous solution of equations 1 and 2 yield,

$E_b = .836$ p.u., $i''_{d_c} = \frac{1.25 - .836}{.5} = .828$ p.u.

(Check): $E_a = .836 - (i_m - i_c)\, Z_1 = .836 -$
$(4 + j1.172)\,(.03 + j.05) = 1.03$ p.u.

Without any condenser the same current surge of $(4 - j2)$ would produce a voltage dip of $E_b = .80$ p.u.

(Check): $E_a = .80 + (.03 + j.05)\,(4 - j2) = 1.03$ p.u.

This clearly demonstrates the meager benefits from a normal condenser for such an installation, for the condenser produced only a 4.5 % change in the voltage during the transient phenomenon from what it would have been with no condenser.

For the reactor plan with a 5% reactor and the same conditions, E_b can be calculated as follows:

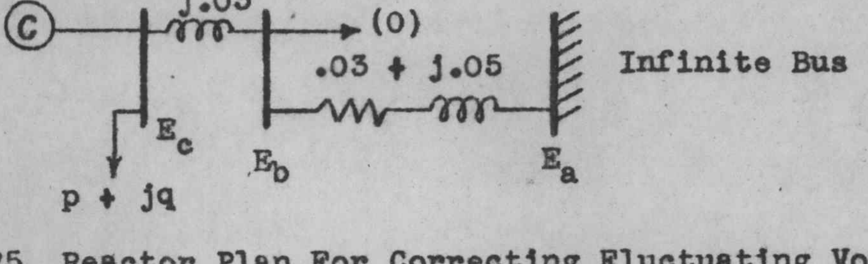


Fig. 25 Reactor Plan For Correcting Fluctuating Voltages.

<u>Normally:</u> $E_b = 1.0 \angle\theta$, $i_m = 1 - j.5$, $i_c = +j.5$

$E_c = E_c \angle 0^\circ$

$E_c \angle 0^\circ = E_b \angle \theta - jx\,(i_m - i_c) = 1.0 \angle \theta - j.05\,(1 - j.5 - j.5)$

$E_c = .999$ p.u.

(Note that the reactor changes the C bus voltage very little during normal operation from its value without the reactor.)

$E_a = .999 + 1.0(.03 + j1.0) = 1.029 + j.1 = 1.035$ p.u.

$E_d'' = .999 + .5 \times .5 = 1.249$ p.u.

<u>During Transient:</u> $i_m = 4 - j2$

$$(1.035 \cos \theta + j1.035 \sin \theta\,) - E_c \angle 0^\circ = (.03 + j.10) \times \left[(4 - j2) + j\frac{(1.249 - E_c)}{.5} \right]$$

$E_c = .747$ p.u., $i_{d_c}'' = 1.006$, $E_b = .823$ p.u.

(Check): $E_a = E_b + (.03 + j.05)\,(i_m + i_{d_c}'') =$

$= .823 + (.03 + j.05)\,(4 - j2 + j1.006) =$

$= 1.035$ p.u.

If the case with only the condenser is compared with this case involving a series reactor, we deduce that some current surges would cause worse fluctuation of E_b in the reactor plan than without the reactor, even though the condenser current in this case exceeds that for just the normal condenser connection. This is particularly true if the surge current has a large real component because the reactor shifts the load current back in phase relationship to E_b and E_a, so that a larger quadrature component of current flows through the line reactance.

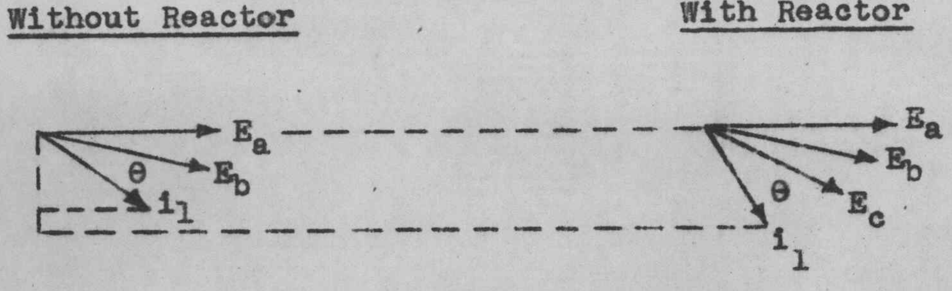


Fig. 26 Reactor Plan Shows Larger Quadrature Component Of Current Than Normal Condenser Application Without Reactor.

This, then, decreases E_b. The next calculation illustrates the effects of a purely reactive load.

Since most current surges result from the rise and support of magnetic fields they represent mostly reactive energy. The most severe surges will be of this nature, such as when an induction motor is started or when a transformer is suddenly excited. For this reason, a case is treated when the current jumps to $-j4$ p.u. With no reactor E_b dipped to .836 p.u. and $i''_{d_c} = .828$ p.u., while with a 5% reactor $E_b = .849$ p.u. The same initial conditions of $E_b = 1.0$, $E_a = 1.0$, and $i_c = j.5$ prevailed in each case. In this case the reactor improved the "B" bus voltage by roughly 1.5%.

A more elegant method for stabilizing the load bus voltage might consist of compensating the condenser reactance with a series capacitor. A case was tried with 20% compensation for the same 5 mva condenser:

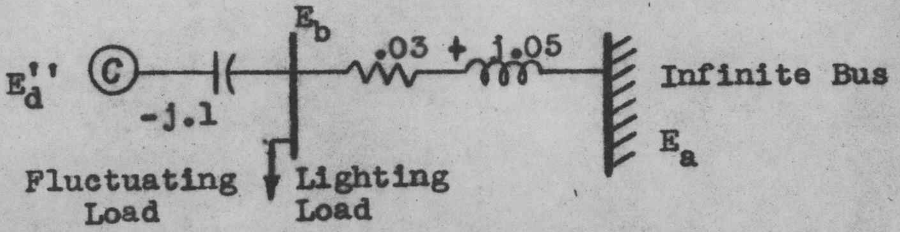


Fig. 27 Circuit For Series Capacitor Plan For Correcting For Fluctuating Voltage.

$x_c = -j.1$ p.u. at 10 Mva

Initially: $i_m = 1 - j.5$, $i_c = j.5$, $E_a = 1.03$ p.u.

$E_d' = 1.0 + .5(.5 - .1) = 1.20$ p.u.

(Note that compensation has lowered the internal voltage in order to preserve the same terminal conditions.)

Transient: $i_m = 4 - j2$ p.u.

$$(1.03 \cos \theta + j1.03 \sin \theta) - E_b = \left[4 - j2 + j\frac{(1.20 - E_b)}{.4}\right] \times (.03 + j.05)$$

$E_b = .843$ p.u., $i''_{d_c} = \dfrac{1.20 - .843}{.4} = .893$ p.u.

(Check): $E_a = .843 + (4 - j2 + j.893)(.03 + j.05)$

$E_a = 1.03$ p.u.

Several values of compensation were tried for the same currents used in the reactor cases. The data from these calculations are plotted below as functions of the amount of compensation, or reactance in the reactor case. Evidently, the reactor scheme manifests some merit for reactive current surges, but it cannot be relied upon to correct voltage depressions caused by sudden surges of real current. On the other hand, the compensated condenser current is impartial to the type of current

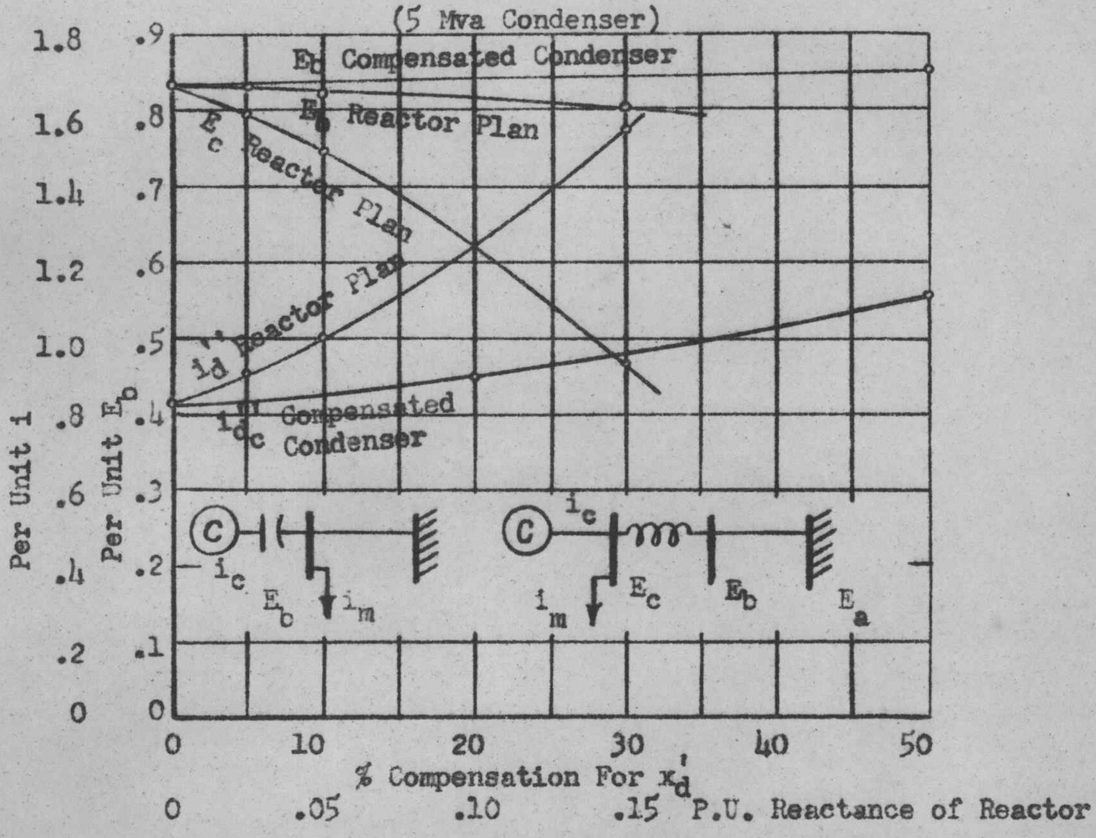


Fig. 28 Comparison of Condenser Currents and Voltages For Series Reactor Plan Versus Series-Capacitor Compensation Assuming, Initially $i_m = 1-j.5$, $i_c = j.5$, and Transient Current $i_m = 4-j2$.

surge and depends only upon the magnitude of the depressed bus voltage. Any depressed voltage condition is, thereby, improved by the compensated or uncompensated condenser. Even 20% compensation does not affect the bus voltage appreciably, although there is some improvement over no compensation. As mentioned earlier, the reason lies mostly in the fact that the condenser reactance compares too high with the line reactance. With even 50% compensation the condenser reactance is still 5 times the line

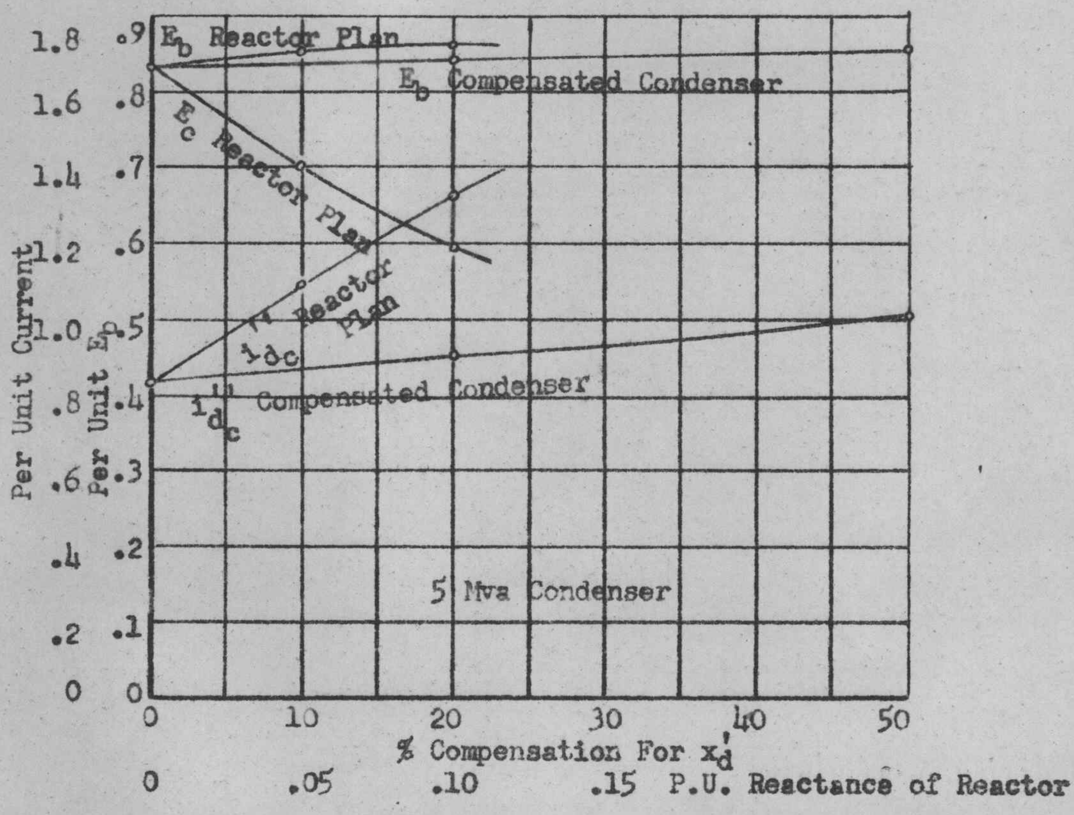


Fig. 29 Comparison of Condenser Currents and Voltages For Series Reactor Plan Versus Series-Capacitor Compensation Assuming, Initially $i_m = -j.5$, $i_c = j.5$, and Transient Current $i_m'' = -j4.0$.

reactance. This fact must be well acknowledged before proposing that a certain condenser be installed to improve flickering voltage conditions. If the hypothetical installation had used a larger condenser then we could expect more improvement in E_b. The case shown in Fig. 30 treats a 25 Mva., 25% reactance machine and a surge current of -j10 p.u. instead of only -j4 p.u. With consideration only to "B" bus voltage a 10% reactor plan transcends the performance of a 40% compensated condenser. The reactor improves the "B" bus voltage by

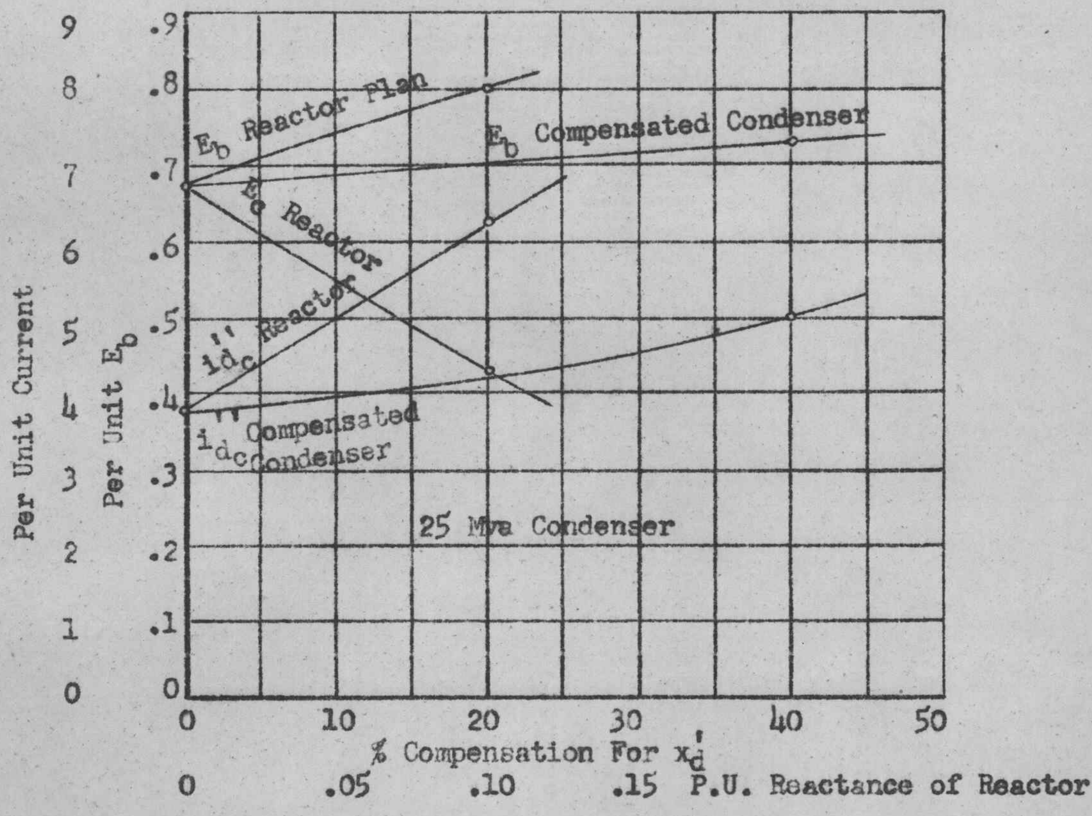


Fig. 30 Comparison of Condenser Currents and Voltages For Series Reactor Plan Versus Series-Capacitor Compensation Assuming, Initially $i_m = -j.5$, $i_c = j.5$, and Transient Current $i_m = -j10.0$.

13% while the compensated condenser improves the voltage by only 6%. However, the reactor plan forces the flickering load bus down to only 43% voltage, which may be quite undesirable for motor operation. From a stability viewpoint, the condenser terminal voltage has declined to only 53% in the compensated condenser case, and, hence would provide a more stable machine than the reactor plan. Both plans, however, further lower the stability limits of the condenser in actual practise, because the normal operating excitation must be lowered in order to preserve the original conditions before the plans were introduced. The compensated condenser case can be made to perform as well and if not better than the other plan by merely compensating the condenser until the condenser current is equal to that for the reactor case. Both cases now possess the same stability approximately, but the compensated condenser has the advantage of better terminal voltages.

The foregoing computations and analysis suggest some of the important points to consider before installing a compensated condenser to correct for flickering voltages. These points might be enumerated as follows:

1. Determine the system impedance.
2. Choose a condenser with low enough subtransient reactance to measurably lower the system impedance when compensated.
3. Compensation can be used to lower the condenser reactance to the approximate value desired, provided a stable machine is assured. Even small hunting conditions are to be avoided as much as possible, although minor hunting may be tolerated in order to correct for bad voltage dips.

If the condenser is allowed to become too elastic by over-compensation then the output current overshoots.

The undesirable effects upon voltage may appear as shown in oscillograms 11 and 12 below:

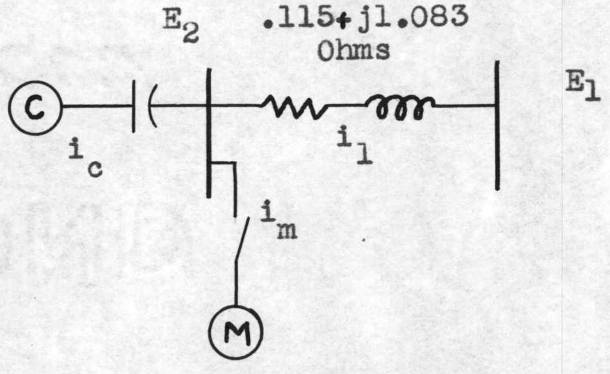
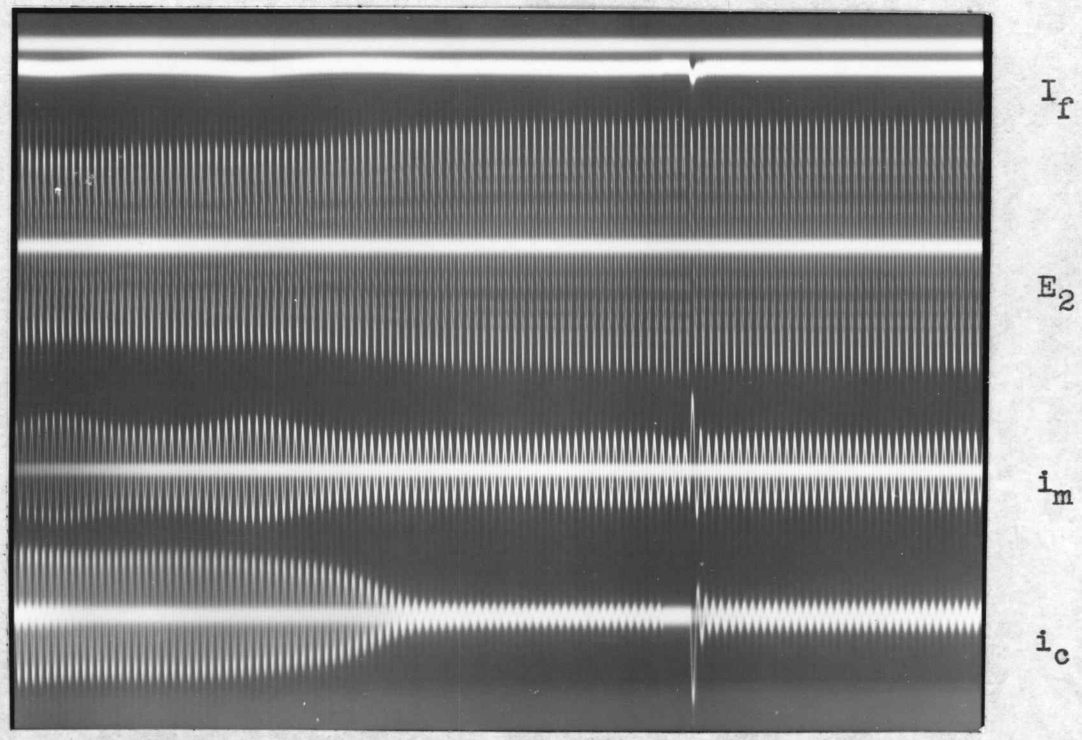
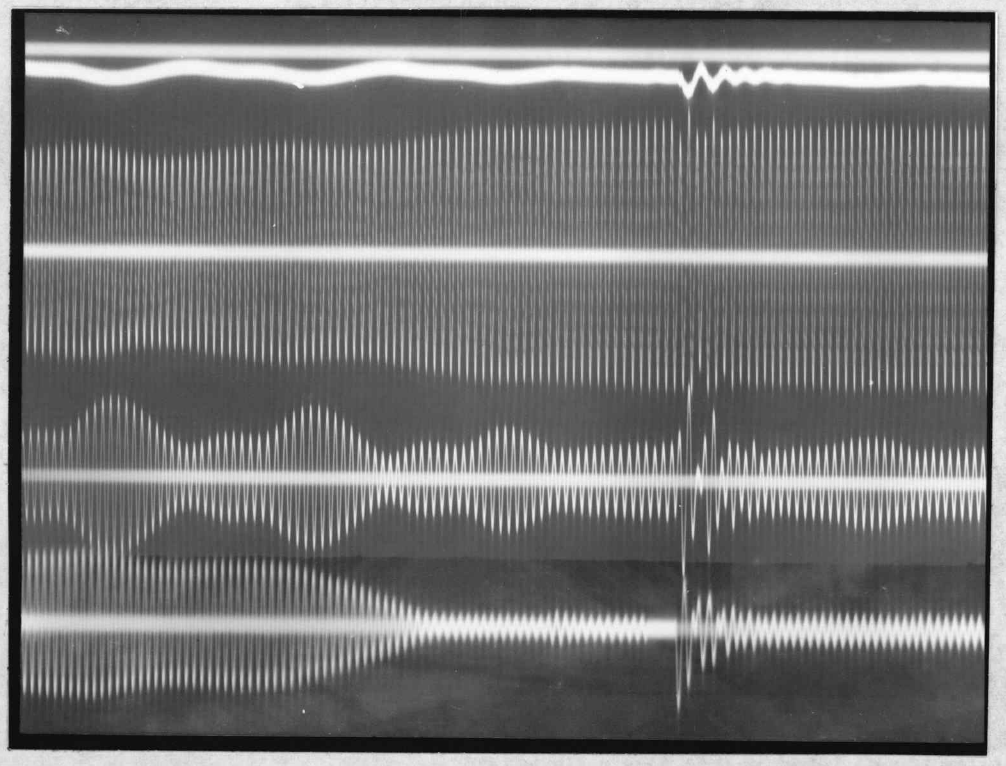


Fig. 31 Test Circuit For Oscillograms 11 and 12.



Oscillogram 11 Sudden Starting of Induction Motor
0% Compensation $R_2 = 0$



Oscillogram 12 Sudden Starting of Induction Motor
90% Compensation $R_2 = 0$
Capacitor Already In Circuit

These oscillograms show the transient instigated by the starting of an induction motor in parallel with a synchronous motor. The portion of the oscillograms displayed caught the time interval during which the induction motor starter was thrown from start to run position. Because the line impedance was higher than the machine subtransient reactance the normal condenser was very effective in stabilizing the bus voltage. In

Table 4

Data For Oscillograms 11 - 12

12.5 Kva General Electric A.C. Generator
Type AHI 4 1800 RPM 3 Phase 60 Cycles
Volts 110/220 Amps. 65.6/32.8 P.F. .8
Excitation 125 Volts 2.5 Amperes
No. 5607090

Oscillogram No.	% Compensation	E_1	E_2	E_3	e_{c_p}	e_{c_s}	i_c	i_m	i_1	I_f	Time
11	0	195.7	231.0	230.0	0	0	19.5	0	19.5	2.5	Before Load
	0	191.0	220.0	219.6	0	0	21.8	4.7	17.3	2.5	After Load
12	90	212.2	248.0	230.0	9.1	40.8	19.3	0	19.3	2.5	Before Load
	90	207.2	238.0	218.0	10.4	46.0	22.4	4.3	17.1	2.5	After Load

circumstances where the line impedance is already larger than the normal condenser reactance the condenser will do a fine regulating job without compensation although some compensation will provide even better regulation. However, in this case the compensation is probably near 90% for subtransient reactance, and the beneficial effects of compensation are masked by hunting and flywheel effects. Note how the bus voltage overshoots and depresses in oscillogram 12. Back in oscillogram 1, with no compensation, the process was smooth and effective. This emphasizes the importance of maintaining a stable machine. In passing, it should be mentioned that oscillograms displaying the starting of motors with a compensated condenser nearly always showed a more irregular and erratic transient than those with uncompensated condenser.

So far in this chapter we have taken the position of the compensated condenser in preference to the reactor plan for stabilizing voltages, but each might have special merits for a particular application. Any proposed installations should be carefully studied with both of these plans in mind initially, and then one should weigh one against the other. The basic distinctions of the two plans are:

1. The compensated condenser stabilizes the load bus voltage, while the reactor plan improves the

distribution bus voltage and harms the load bus voltage.

2. The capacitor carries only condenser current while the reactor must withstand full line current.

3. The reactor more effectively suppresses condenser terminal voltage because its potential drop results from full line current, not just condenser current.

Both plans operate on the principle that condenser current increases when terminal voltage is depressed or visa versa. Obviously, there is no advantage in either plan for steady-state operation because the condenser output can always be controlled by the excitation system. However, it might be wise to utilize condensers of slightly lower than normal voltage rating for these applications in order to maintain high internals in the machines and improve their stability. For the same kva machine this means a lower reactance condenser.

In order to describe the performance of the compensated condenser another powerful tool with which to combat flicker conditions has been ignored. Series line capacitors have been very successfully utilized for such purposes. In the previous examples a series capacitor would have performed commendably.

<u>10 Mva Base</u>

Let $x_c = .4x_l = -j.02$ per unit;

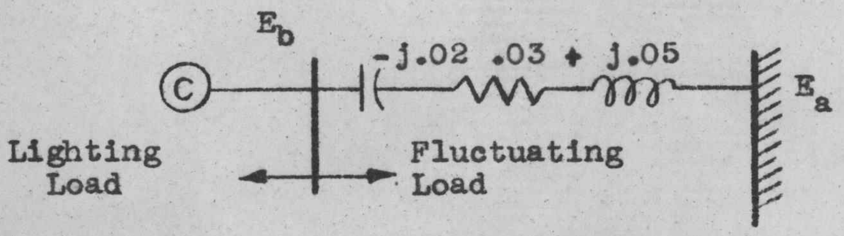


Fig. 32 Series Capacitor Plan For Fluctuating Voltages.

__Initially:__ $i_m = -j.5 \quad i_c = j.5 \quad x_d'' = .5$ per unit

$$E_d'' = 1.0 + .5 \times .5 = 1.25 \text{ p.u.}$$

__Transient:__ $i_m = -j4.0 \quad E_a = 1.0 \underline{/\theta}$

$$\cos\theta + j \sin\theta - E_b = \left(-j4 + j\,\frac{1.25 - E_b}{.5}\right)(.03 + j.03)$$

By the method of page 88, $E_b = .900 \qquad i_d'' = .700$ p.u.

(Check): $E_a = .900 + (-j4 + j.7)(.03 + j.03) = 1.00$ p.u.

With 40% compensation of line reactance E_b dipped to .900 p.u. voltage during the initial transient, whereas, the same condenser compensated 50% allowed E_b to dip to .85 p.u. under the same conditions. Evidently, much can be said for series compensation of line reactance as a method for reducing system impedance to the load bus. Most cases would, perhaps, be most adapted to this solution for flicker voltages, but some cases would not. When many lines feed the load bus, all of high impedance, then this method may break down in favor of one of the two earlier plans described. The particular installation will determine the best solution for flicker voltages.

Chapter VIII

Condenser and Capacitor Protection

One cannot expect to receive the sudden release of reactive energy from the synchronous condenser when the capacitor is inserted without some repercussions in the machine. The insertion of the capacitor appears somewhat like a sudden partial short-circuit to the condenser. The current in the stator or armature winding immediately rises to satisfy the condition $i_d'' = \frac{E_d'' - V_t'}{x_d''}$. Since the flux linkages with the field coils cannot instantaneously change, a transient uni-directional current is induced in the field winding to compensate for the demagnetizing flux produced by the large armature current. (Note the field current in oscillograms 11 and 12.) The sudden large currents in a strong magnetic field exert strong mechanical forces and torques between windings and between stator and rotor. As a result the armature coils, frame, and rotor incur great mechanical shock. Therefore, the condenser must also be of rugged enough construction to endure frequent mechanical stresses approaching short-circuit conditions. The actual terminal voltage in a normal operation with compensation will probably not be allowed to go below 20 or 30% normal voltage, so that the mechanical shock will be somewhat less than for normal machine short-circuit conditions. However, a bus fault would impose an especially harsh condition, because the machine impedance would be less than under normal short-circuit conditions. To obviate unduly austere conditions it becomes necessary to provide voltage activated relaying which will prevent compensation if the bus voltage is already below approximately 40%. If this safety measure is installed there is every reason to believe the average condenser can shoulder the burden of compensation. Laboratory experience has taught that compensated condensers do not experience nearly as great a shock as under normal short-circuit conditions. Anti-hunt or amortisseur windings and high inertia are very desirable features for compensated condensers. Any of the small machine oscillograms of previous chapters illustrate how easily compensation can lead to hunting of low inertia machines.

We already have considerable experience with series capacitors which should facilitate the engineering of the proposed type of installation. The capacitor must be provided with a shunting device, usually a spark gap, to protect it during fault and excessive line current conditions. Thus, for stability purposes the compensating capacitor is shunted by a breaker, which normally is closed, and an arc gap, which protects it while in the circuit. Some economy for this type of application may

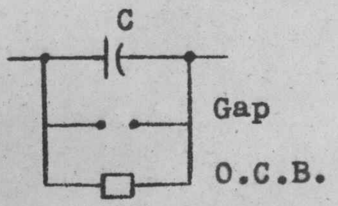


Fig. 33 Series Capacitor Protective Circuit.

be realized because the capacitor does not remain in the circuit longer than about 3 seconds or 3 x 60 = 180 cycles. For continuous line compensation the operation must not exceed the capacitor ratings, but on short times General Electric and Westinghouse capacitors may be worked to twice rated voltage for 10,000 cycles. Assume a 30 mva condenser, $x_d' = 40\%$, and that the minimum voltage for condenser stability is .2 per unit. Assuming initial bus voltage was 1.0 p.u., then $E_d' = 1.0 + .4 = 1.4$ p.u. Maximum condenser current allowed is $i_d' = \frac{1.4 - .2}{.4} = 3.0$. If the terminal voltage is allowed to go as low as .4 per unit then, $x_c = \frac{.4 - .2}{3.0} = .067$ p.u. $= \frac{.067}{.40} \times 100 =$ 16.75% compensation is the maximum allowable compensation. The capacitor rating is $e_c \times i_d' /4 = .2 \times 3/4 = .15$ p.u. = 4.5 mva, since twice rated voltage means the capacitor can permit twice rated current. The spark gap would be set to flash over at approximately 3 times rated capacitor voltage or $\frac{3}{2} \times .2 = 30\%$ voltage. If the spark gap is set too low minor voltage oscillations or harmonics are liable to cause excessive spurious operations.

It seems very probable that the sudden insertion of a capacitor into an inductive circuit might develop unforeseen and obscure sub-synchronous oscillations. This would possibly alter much of our previous theory. The fundamental circuit below can be analyzed mathematically on a transient basis with these approximately valid assumptions:

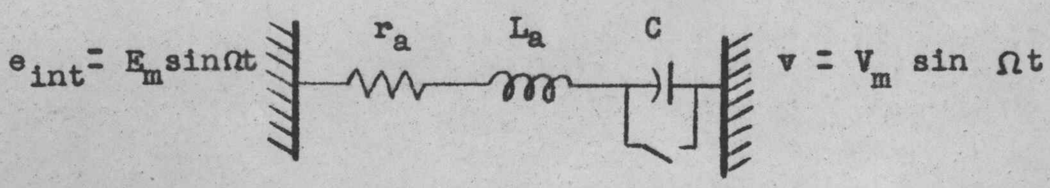


Fig. 34 Equivalent Circuit of Compensated Condenser

1. Bus voltage is assumed to remain constant after the initial depression.
2. Internal voltage is assumed constant by the theorem of constant flux linkages.
3. Saturation and the consequent effects upon leakage reactances in the armature and rotor circuits are neglected.
4. The armature circuit is treated independent of the rotor circuits as a simple D.C. resistance and a leakage reactance. (Proof of the validity of this assumption follows.)
5. The armature D.C. resistance per phase, r_a, and

average armature leakage reactance in the presence of a closed field winding are the circuit parameters to be used. X_a is closely approximated by the negative sequence reactance, x_2, of the machine, which is the value suggested for this application.

According to the above assumptions the circuit equation at any instant before capacitor insertion is:

$r_a i + L_a\, di/dt = e_{int} - v'$, where (1)

$v' = V_m' \sin \Omega t$

$r_a = R_{d.c.}$ of the armature per phase, ohms

$e_{int} = f\ (t)$

$L_a = x_2 / 377$ henries for a 60 cycle machine

The solution of this linear differential equation of the first order is,

$i = C\, e^{\frac{-r_a}{L_a} t}$ + (Particular integral or steady-state solution) (2)

The particular integral would be a simple steady-state expression like $\frac{E}{Z} \sin(\ t + \theta + \phi)$, except that the rotor induces voltages in the armature which decay exponentially. From experience we know the correct expression for the particular solution is:

$$\left\{ \left(\frac{E_d'' - V_m'}{x_d''} - \frac{E_d' - V_m'}{X_d'} \right) e^{\frac{-r_{am}}{L_{am}} t} + \left(\frac{E_d' - V_m'}{x_d'} - \frac{E_d - V_M'}{x_d} \right) x \right.$$

$$e^{\frac{-r_f}{L_f}t} + \frac{E_d - V_m'}{x_d}\Big\} \sin(\Omega t + \theta + \phi) \quad , \tag{3}$$

where all quantities are phase values;

E_d' = voltage behind transient reactance = $V_o + i_o x_d'$ for the condenser.

E_d'' = voltage behind subtransient reactance = $V_o + i_o x_d''$.

E_d = voltage behind saturated synchronous reactance = $V_o + i_o x_d$.

V_o = maximum terminal voltage to neurtral before voltage depression.

V_m' = maximum voltage to neutral after depression.

r_{am} = equivalent D.C. resistance of the amortisseur or damper windings.

L_{am} = inductance of amortisseur or damper windings.

r_f = D.C. resistance of main field circuit.

L_f = main field inductance.

$x''d$, x_d', x_d = machine subtransient, transient, and saturated synchronous reactances.

θ = angle of applied voltage wave at which voltage transient occured.

ϕ = power factor angle.

(In addition, this equation neglects resistance except to determine decrement factors and assumes that V_m and all internal voltages are in phase, which is practically true for large leading current and low armature resistance.)

ϕ is nearly $\frac{\pi}{2}$ for a synchronous condenser with over-excitation. Also, the largest D.C. offset of the armature current results if the transient occurs when energy in the circuit's inductance is normally greatest or when i is a maximum. This occurs in the synchronous condenser when the armature and field poles are aligned, $v = e_{int} = 0$, and hence, for $\theta = 0$.

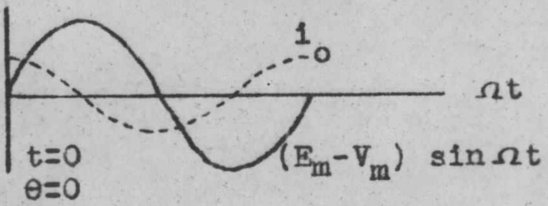


Fig. 34 Phase Relationship of Condenser Line Current and Phase Voltage.

The current expression may be completely solved for constants,

$\sin(\Omega t + 0 + \pi/2) = \cos\Omega t$

$$i = C\, e^{\frac{-r_a}{L_a}t} + \left\{\text{Particular Integral}\right\} \cos\Omega t \qquad (4)$$

at $t = 0$, $\theta = 0$, $i = i_o$ = maximum steady-state current before the transient. Therefore,

$$i_o = C + \frac{E_d'' - V_m'}{x_d''}\,, \qquad C = i_o - \frac{E_d'' + V_m'}{x_d''}\,.$$

Hence, complete armature current equation is

$$i_a = \left(i_o - \frac{E_d'' - V_m'}{x_d''}\right) e^{\frac{-r_a}{L_a}t} + \left\{\text{Particular Integral}\right\} \cos\Omega t \quad (5)$$

Between the time that the condenser terminal voltage instantaneously decreases and the time the capacitor is inserted the expression above completely describes the armature current. Upon opening of the circuit breaker which shunts the series capacitor the differential equation becomes:

$$r_a i + L_a \frac{di}{dt} + \frac{i}{c} \int i \, dt = e - v' = f(t) - v' \qquad (6)$$

The auxiliary equation becomes $(L_a p^2 + r_a p + \frac{1}{c})i = 0$

or $\lambda^2 L_a + \lambda r_a + \frac{1}{c} = 0$, which has the roots (7)

$$\lambda_1, \lambda_2 = -\frac{r_a}{2L_a} \pm \sqrt{r_a/4L_a^2 - 1/L_aC} = -\alpha \pm j\omega \text{, where} \qquad (8)$$

$\alpha = -r_a/2L_a$ and $\omega = \sqrt{1/LC - r_a^2/4L_a^2}$

The complete current expression is

$$i = K_1 e^{\lambda_1 t} + K_2 e^{\lambda_2 t} + \text{(Particular Integral.)} \qquad (9)$$

This circuit is oscillatory if $\frac{1}{LC} \geq \frac{R^2}{4L^2}$

For the test machine;

L_a = armature leakage reactance = $\frac{x''_d}{377}$

= $.100 \times \frac{3.075}{377}$ = .000816 henry.

r_a = .069 Ohms D.C.

(The subtransient reactance is substituted for the armature leakage reactance because x_2 is not immediately available. The direct-axis subtransient reactance closely approximates the armature leakage reactance but is slightly lower than the average leakage reactance approximated by $(x_q'' > x_d'')$ $\quad x_2 = \frac{x_d'' + x_q''}{2}$. If the circuit is critically damped then, $1/LC = r_a^2/4L_a^2$, or $\frac{1}{C} = r_a^2/4L_a$, and $C = \frac{4L_a}{r_a^2}$

$$C = \frac{4 \times .000816}{.069^2} = .686 \text{ farads, } x_c = .00391$$

The maximum compensation to just prevent oscillation is

$$\frac{x_c}{x_d'} = \frac{.00391}{.680} \times 100 = .575 \text{ per cent.}$$

Evidently, the circuit will be oscillatory for all practical amounts of compensations. In the normal case L_a includes possibly some line and transformer reactance, because the infinite bus condition may not be realized directly at the condenser bus, but at some distance between it and the generating plants. Also, we should not hasten to identify the oscillations predicted here as the oscillations common to practically all the oscillograms of chapter V. There can be no doubt that the approximately 4 cps oscillation in the oscillograms was due to hunting of the machine. First, the oscillations appeared whether or not compensation was used, if the transient shock to the system were severe enough. Second, the time constant was much too large tobe anything except hunting.

Since the condenser bus voltage did not remain constant in the laboratory the infinite bus must be considered at the sending-end of the transmission line. With this assumption,

$Z_{line} = .142 + j1.638$ ohms

$x_a = .3075$ ohms

$r_a = .069$ ohms

$L_{total} =$ total circuit inductance $= \frac{(1.638 + .3075)}{377}$

$= .00516$ henries

$r_t = .069 + .142 = .211$ ohms

The time required for the oscillations to decrease to 36.8% of their initial value is $\frac{1}{\alpha} = 2L_t/r_t = \frac{2 \times .00516}{.211}$

$= .049$ seconds $= 3$ cycles. (Notice that the major oscillations on any oscillogram decay a negligible amount in this time. Thus, the major oscillations are due to hunting of the machine, as differentiated from the phenomenon described here. Now on oscillograms 6, 7, and 8, which depict cases when the capacitor is inserted, a feeble oscillation on the condenser current wave manifests itself during the first five or so cycles after capacitor insertion. This oscillation modulates the 60 cycle current at about 15 cps as opposed to the 4 cps modulation imposed by hunting of the machine. After 5 cycles the oscillation has disappeared. In oscillogram 8 the compensation was 83% and if we use 83% compensation as an equivalent capacitor with no transformer, then,

$x_c = .83 \times .221 \times 3.075 = .564$ Ohms

$$C = \frac{1}{.564 \times 377} = .00471 \text{ farads}$$

$$f_o = \frac{w}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{1}{L_tC} - \frac{r_t^2}{4L_t^2}} = \frac{1}{6.28}\sqrt{\frac{1}{.00516 \times .00471} - \frac{.211^2}{4 \times .00516^2}}$$

f_o = 32.2 cycles per second.

As will be shown later, this oscillation coupled with the 60 cycle current engenders a modulation frequency equal to: $\frac{60 - f_o}{2} = \frac{60 - 32.2}{2} = 14$ cps.

This checks very well with the observed frequency of variation of the envelope of condenser current, about 15 cps. Note that the first several cycles give rise to abnormally large current, about 1 3/4 times the final steady-state current.

Before completing the solution for the condenser current with compensation we wish to satisfy the criticism that presence of the field winding and additional rotor circuits influence the character of the oscillation. Aside from the effects upon magnitude of current the oscillation frequency, f_o, andattenuation are practically inert to field effects. Consider the circuit following in which the field windings are simulated by an equivalent closed secondary winding, which possesses mutual coupling with the armature circuit.

The differential equations are:

$$(R_1 + L_1p + \frac{1}{Cp})\, i_1 - L_{12}pi_2 = e_{int} - v \qquad (9)$$

$$L_{12}i_1 - (L_2p + R_2)\, i_2 = 0 \qquad (10)$$

Let L_1 = armature leakage reactance - line reactance

L_2 = field leakage reactance

L_{12} = mutual inductance

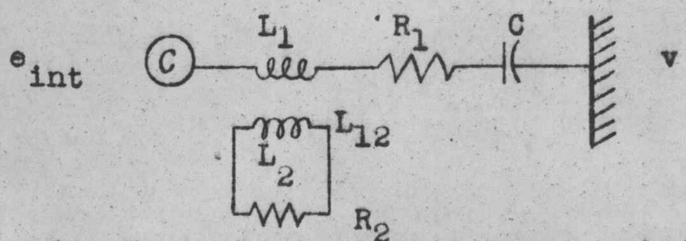


Fig. 36 Equivalent Circuit For Coupled Armature and Field Circuit.

The differential equations are:

$$(R_2 + L_1 p + 1/Cp)i_1 - L_{12} p i_2 = e_{int} - v \qquad (9)$$

$$L_{12} i_1 - (L_2 p + R_2) i_2 = 0 \qquad (10)$$

The auxiliary equation is, (11)

$$\lambda^3 (L_1 L_2 - L_{12}^2) + \lambda^2 (R_1 L_2 + R_2 L_1) + \lambda (R_1 R_2 + L_2/C) + R_2/C = 0$$

which is a third-order differential equation having three roots. At least one of the roots must be real.

$L_1 = L_t = L_{line} + L_a = .00516$ henries.

$R_1 = R_t = .211$ ohms D.C.

$C = .00471$ farads (83% compensation)

R_2 = D.C. resistance of field = $\dfrac{125 \text{ rated volts}}{4.7 \text{ rated amps.}}$ = 26.6 ohms

$L_2 = R_2 \times$ (Time constant of field) $= R_2 \times T_d' = 26.6 \times .046$

$= 1.222$ henries.

L_{12} = leakage reactance between field and armature circuits and closely approximated by $x_d' = .680/377 = .0018$ henries.

By substituting these constants in equation (11) successive

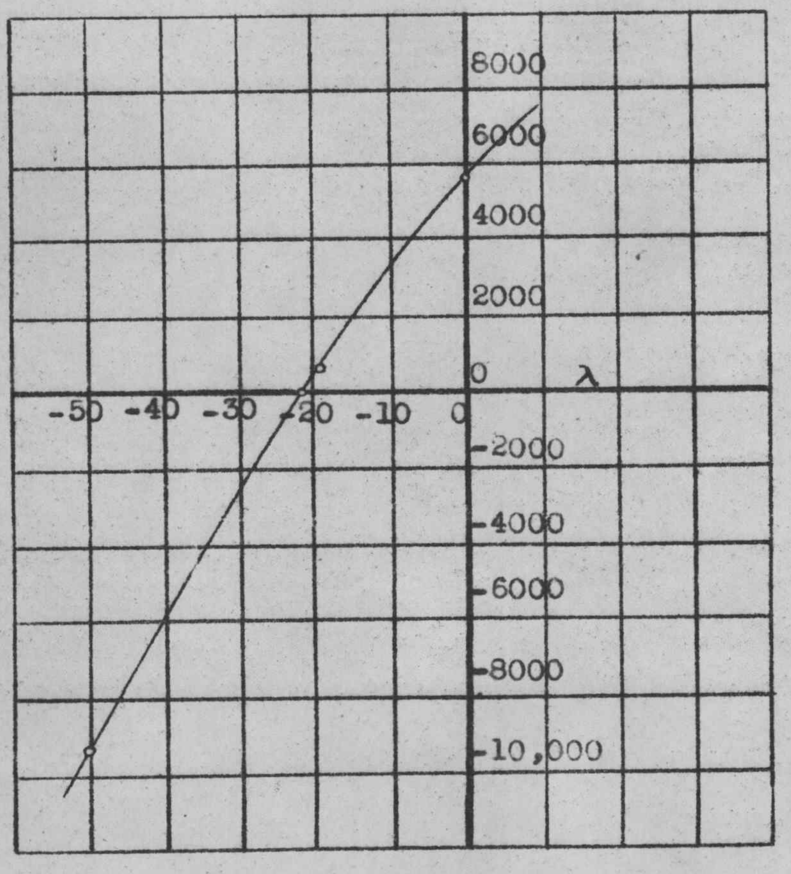


Fig. 37 The Real Root of

$$f\ (\lambda) = .0063\,\lambda^3 - .359\,\lambda^2 - 265.62\,\lambda - 5650$$

approximations provides $\lambda_1 = -21.6$ as the one real root (see Fig. 37). Division of ($\lambda_1 - 21.6$) into the cubic provides the quadratic,

$(\lambda_1 - 21.6) \times (.0063\lambda^2 + .259\lambda + 260) = 0$, from which

$\lambda_2, \lambda_3 = -\alpha \pm jw = -20.6 \pm 202$, and $f_o = 32.2$ cps.

A comparison of results is shown below:

	α	f_o, cps
Solution neglecting field windings:	20.5	32.2
Solution with an equivalent field winding:	20.6	32.2

All that the introduction of the field winding contributes is another decaying D.C. component which actually does not occur, because the field rotates synchronously with respect to the armature m.m.f. A D.C. component is introduced in the field, however, by the sudden change of m.m.f. in the armature windings. Also, the D.C. component in the armature induces an A.C. voltage in the field winding. Yet, the field does not influence the frequency or attenuation factor for the oscillation described above.

Since the single circuit adequately represents the machine, it will be utilized to obtain the complete solution for condenser current with compensation. This may be written as:

$$i = K_1 e^{\lambda_1 t} + K_2 e^{\lambda_2 t} + \left\{\text{Particular Integral}\right\} \times \sin(\Omega t + \theta + \phi) \qquad (12)$$

Now, if t is to be measured from the instant the capacitor enters the circuit, t_g is the time between the initial voltage depression and the time of capacitor insertion, p.f. equals 0 or $\phi = 90^\circ$; $K_1 e^{\lambda_1 t} + K_2 e^{\lambda_2 t}$ may be expressed in sinusoidal form as $A e^{-\alpha t} \sin(\omega t + \psi)$. Then,

$$i = A e^{-\alpha t} \sin(\omega t + \psi) + \left\{\text{Particular Integral}\right\} \times \cos(\Omega t + \theta) \qquad (13)$$

Further simplification results if it is assumed that the breaker, which shunts C, can interrupt only on a current zero or for $\theta = \frac{\pi}{2}$ or $-\frac{\pi}{2}$. (Assume $\theta = +\frac{\pi}{2}$). Due to the fact that some arc drop appears across the breaker contacts before complete current interruption, this assumption is only approximate. With this assumption equation 13 becomes, (14)

$$i = A e^{-\alpha t} \sin(\omega t + \psi) + \left\{ \text{Particular Integral} \right\} \sin \Omega t$$

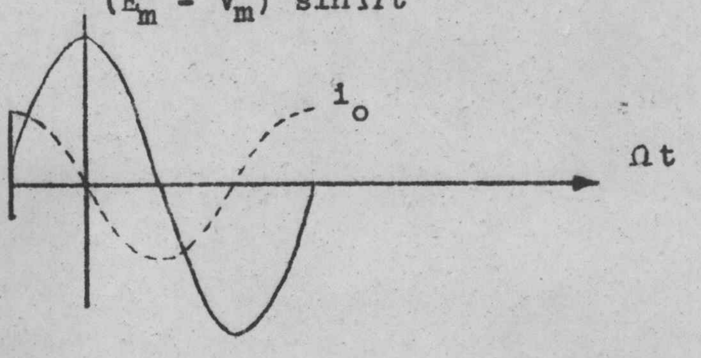


Fig. 38 Phase Relationship of Condenser Line Current and Phase Voltage

The current is a sine function only because t is now measured from $\pi/2$ of the applied voltage wave. Two conditions will permit evaluation of the constants A and ψ.

At $t = 0$, $i = 0$, and if we assume the capacitor had little time to charge during the arc-interruption process of the breaker, $Q = \frac{1}{p} i = 0$. Substituting (15) in (14) at $t = 0$, $0 = A \sin(\psi + 0)$; $\psi = 0$, since $A \neq 0$. A is not so easy to determine as in the simple case with only R and L because A can only be determined from initial conditions involving the unknown function f (t) in equation (6) on page 108. However, A can be fairly accurately determined, if at $t = o$ we consider the circuit to consist of R,L,C and two constant sinusoidal voltages, e_{int} and v'. Actually e_{int} decays with time, but this can be neglected for the first instants. Evaluate the normal condenser current that would flow at time t_g after the initial voltage depression. Label this i_o. Then the equivalent voltage behind leakage reactance at this moment is $e_o = v' + i_o x_a$ and is at a maximum, since $\theta = \frac{\pi}{2}$.

Rewrite the primary equation as,

$$Ri + Lpi + \frac{1}{Cp}\, i = e_o - v' = (E_o - V_m') \sin (\Omega t + \theta) \qquad (16)$$

At $t = 0,\ i = 0,\ \frac{1}{p}\, i = 0,\ \ \theta = \pi/2$

Hence, $L_a pi + 0 + 0 = E_o - V_m'$

$$pi = \frac{E_o - V_m'}{L_a} \qquad (17)$$

Differentiating equation (14) and substitution of (17) at $t = 0$ gives,

$$pi = \frac{E_o - V_m'}{L_a} = -A\alpha e^{-\alpha t} \sin (\, wt) + Aw\, e^{-\alpha t} \cos (wt)$$
$$- \Omega \left(\frac{E_o - V_m'}{x_a - x_c}\right) \cos \Omega t \qquad (18)$$

$$\frac{E_o - V_m'}{L_a} = 0 + Aw + \Omega\left(\frac{E_o - V_m'}{x_a - x_c}\right)$$

$$A = \frac{E_o - V_m'}{wL_a} - \frac{\Omega}{\omega}\, \frac{E_o - V_m'}{x_a - x_c} = -\frac{(E_o - V_m')}{x_a - x_c}\, \frac{\Omega}{\omega} \times \frac{x_c}{x_a} \qquad (19)$$

A is the maximum value of the oscillation, and apparently has a wide range of values depending upon the ratio

$\frac{x_c}{x_a} \times \frac{\text{applied frequency}}{\text{resonant frequency}}$. In our case, $\frac{\Omega}{w} = 60/32.2 = 2$ approximately;

$x_c = .564$ ohms $\qquad x_a = 1.946$ ohms

Since $\frac{E_o - V_m'}{x_a - x_c} = i_d''$, $A = -\frac{\Omega}{w} \times \frac{x_c}{x_a} \times I_d''$.

$A = -2 \times \frac{.564}{1.946} \times I_d'' = -.578\, I_d''$,(where I_d'' is the maximum value of the current wave.)

This states that the oscillation has a maximum amplitude .578 times the amplitude of the normal subtransient current wave at this instant. The complete current expression after compensation is, (21)

$$i = -.578\, I_d''\, e^{\frac{-r_a}{L_a}} \sin wt + \left\{\text{Particular Integral}\right\} \sin \Omega t$$

(Resistances have been neglected in calculation of impedances.)

The actual character of the current wave may not be recognized from the expression above, but simple trigonometric relations reveal the hidden wave shape. For the moment let the complex coefficients be constants A and B. Then, $i = A \sin wt + B \sin \Omega t$. This expression readily transmutes into the form, (22)

$$i = 2\, k \cos \theta \left\{\cos\left[\frac{(\Omega - w)t}{2} - \pi/4\right] \cdot \cos\left[\frac{(\Omega + w)t}{2} - \frac{\pi}{4}\right]\right\}$$

where $k = \sqrt{A^2 + B^2}$ and $\theta = \tan^{-1}\frac{A}{B}$. This now is recognized as a modulated wave, where the higher frequency is an average of the applied and oscillation frequency, and the modulating frequency is one-half the difference frequency. We previously employed this relation to verify the observed wave shape. (See appendix for derivation.)

In the electronics and power fields alike, spurious oscillations can become very troublesome and usually must be curbed somehow. In this case a simple resistor in shunt with the series capacitor offers the best solution. The resistance can be shown to have little effect upon the frequency of oscillation for practical resistance values, but commendable improvement in the rate of decay of the transient oscillation evolves from its use. Introduction of R_2 alters the primary differential equation to,

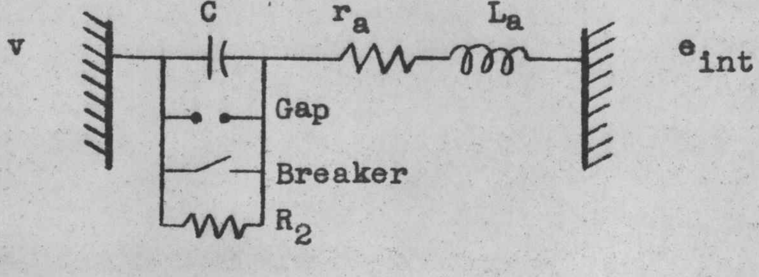


Fig. 39 Equivalent Circuit Illustrating Use of Damping Resistor.

$$\left(r_a + L_a p + \frac{r_a}{CR_2 p + 1}\right) i = e_{int} - v' \qquad (23)$$

The auxiliary equation is,

$$\lambda^2 L_a C R_2 + \lambda (L_a + C r_a R_2) + r_a + R_2 = 0 \qquad (24)$$

$$\lambda_1, \lambda_2 = -\frac{L_a + C r_a R_2}{2 L_a C R_2} \pm \sqrt{\frac{(L_a + C r_a R_2)^2 - 4 L_a C R_2 (r_a + R_2)}{2 L_a C R_2}}$$

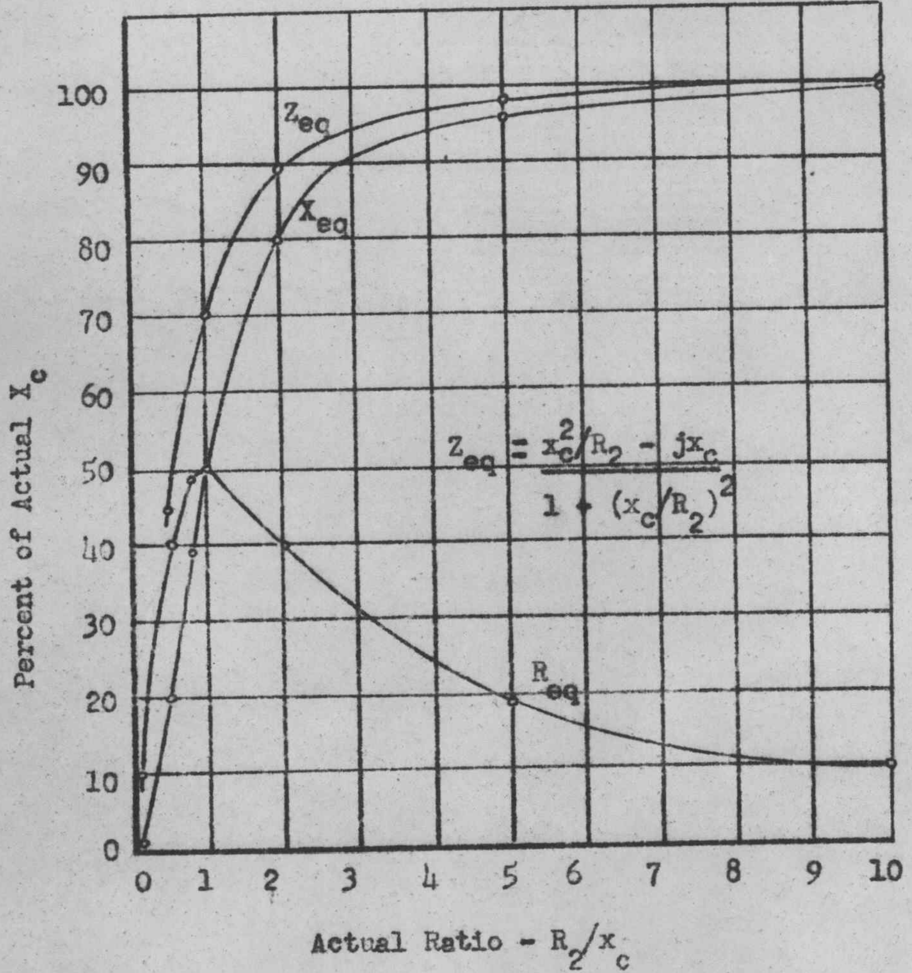


Fig. 40 Equivalent Series Impedance Formed By C and R_2 of Fig. 39 As a Function of The Ratio R_2/x_c.

The parallel circuit of C and R_2 has an equivalent series impedance

$$Z_{eq} = \frac{R_2\,(-jx_c)}{R_2 - jx_c} = \frac{x_c^2/R_2 - jx_c}{1 + (x_c/R_2)^2} \quad . \tag{25}$$

If R_2 is substituted as a ratio with respect to x_c, the curve of Fig. 40 results. Above $R_2/x_c = 10$, R_2 has negligible effect upon the effective circuit impedance or reactance, x_{eq}. At $R_2 = 10x_c$, one-tenth the line current flows through the resistance R_2. For a 30 mva condenser at 13.8 kv., $I_1 = \frac{30 \times 10^6}{3 \times 13.8 \times 10^3} = 1256$ amperes, and

125 amperes flow through R_2. If $x_c = .5\ x_d'$ and $x_d' = 40\%$, then, $R_2 = 10.5 \times .4 \times \frac{13.8^2}{30} = 12.7$ ohms. R_2 must dissipate $125^2 \times 12.7 = .98.5$ kw. If $R_2 = 100x_c$, then Power $= 12.6^2 \times 127 = 20.2$ kw. Evidently, R_2 must possess considerable current carrying capacity even though the interval of time during which R_2 is used only amounts to several seconds.

Next are shown the effects of varying values of R_2 upon the frequency and attenuation ofthe transient oscillation for a 30 mva condenser. Assume the following,

$x_d' = 40\%$ on 30 mva base at 13.8 kv.

$x_c = .5\ x_d' = 1.27$ ohms

$r_a = .00775$ ohms D.C. (Values for r_a and L_a are from Westinghouse book for 30 mva condenser.)

$L_a = x_2/377 = 1.523/377 = .00404$ henries.

The curves of Fig. 41 on the next page were compiled by substitution of the above constants in equation (24) and using $x_eq = -\frac{jx_c}{1+ (x_c/R_2)^2}$ to determine the amount of capacitance for 50% compensation. Clearly R_2 affects f_o very slightly until a ratio of $R_2/x_c = 1$. This is, however, an impractical region of operation because of the size resistor required. Similarly, experiences its greatest

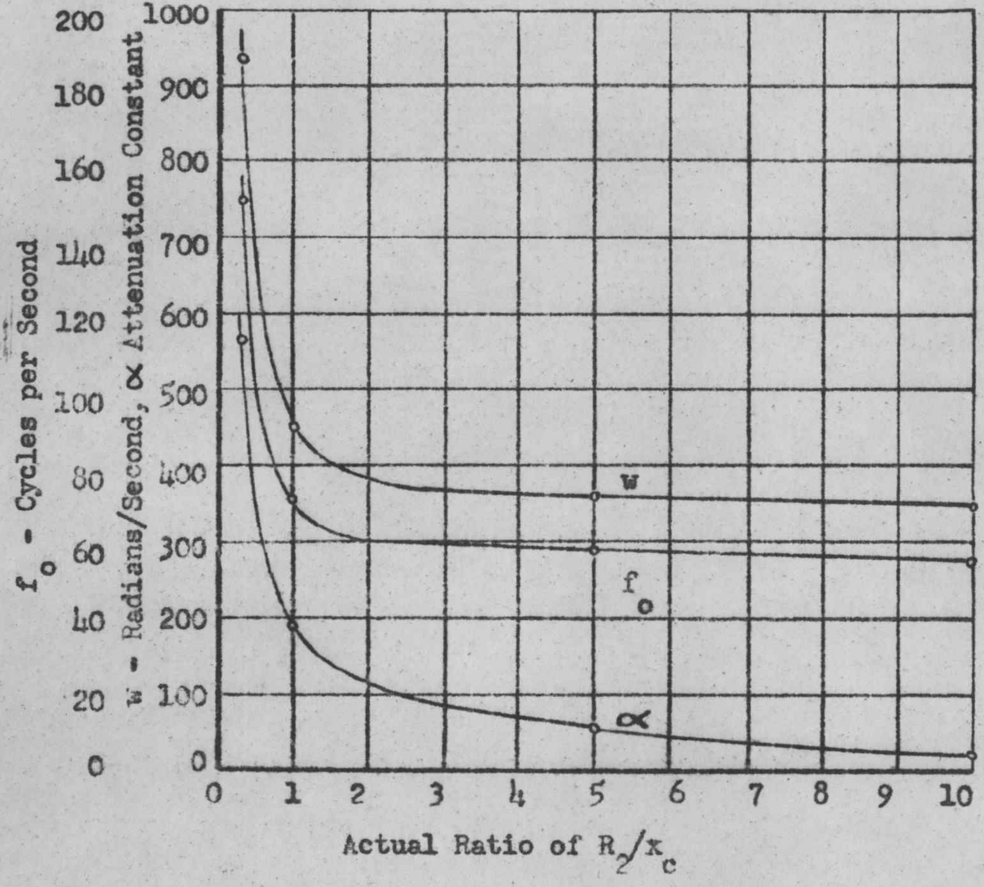


Fig. 41 Effect of R_2 Upon Natural Frequency of Oscillation of Circuit Shown In Fig. 39.

change below $R_2/x_c = 1$, but displays considerable improvement even for $R_2/x_c = 10$. At $R_2/x_c = 10$, $\propto = 19.75$ and when $R_2 = \infty$, $\propto = .898$, which means the transient oscillation has decayed in approximately 1/20th the time required when $R_2 = \infty$.

As the compensation of any one condenser increases the capacitance required diminishes, and the frequency of transient oscillations increases. The attenuation constant remains independent of compensation as long as a fixed

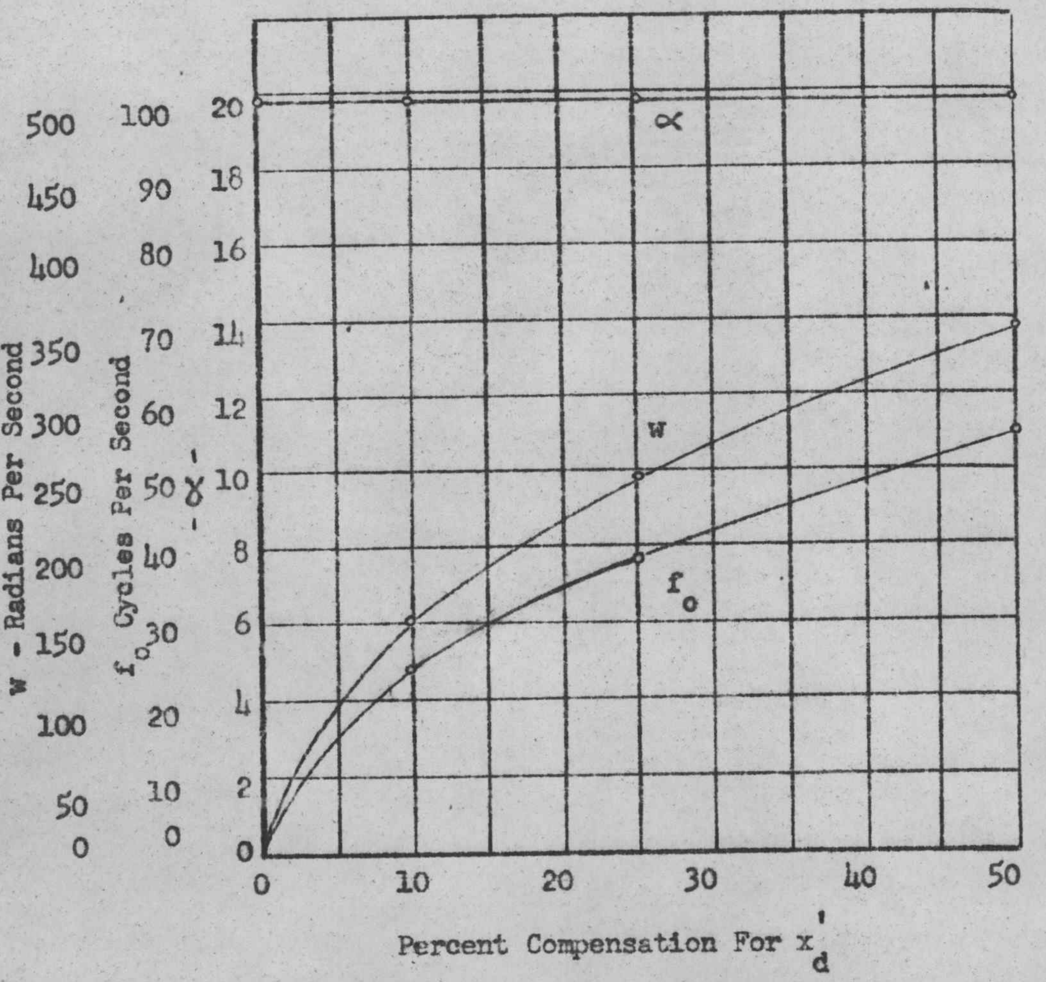


Fig. 42 Affect of Compensation On Natural Frequency of Oscillation of a Compensated Condenser; $x_d' = 40\%$, 30 Mva, and $R_2/x_c = 10$.

ratio of R_2/x_c is maintained. These points are illustrated in Fig. 42 for a 30 mva condenser with $R_2/x_c = 10$. The graph was compiled from substitution in equation (24).

Our investigation of the possible transient oscillations escorting insertion of the series capacitor indicates these oscillations cannot be avoided by any practical supplements to basic engineering design of the compensated condenser circuit. A shunt resistor of as low a resistance value permissible, considering the cost for resistors of high power rating, immensely decreases the time duration of the transient but has negligible effect upon the magnitude and frequency of the transient for $R > 10\ x_c$. If costs permit, the resistor could possibly attain a minimum value of $5x_c$, and then would be limited by only the appreciable lowering of the equivalent series compensation and increase of circuit losses. Empirical evidence has shown no particularly severe current surges from these oscillations which would greatly increase the hazards of such an installation. However, the one example showed the oscillation could have a magnitude of .58 times the instantaneous current just before insertion of the capacitor. The current components are in phase, and the condenser current will also increase above what it was before compensation due to subtransient and transient current components caused by the lower circuit impedance. Hence, if the new subtransient current goes to twice normal then total current would be about 2.5 times normal, and the capacitor rating and spark gap should be correctly coordinated accordingly. The particular case will declare its own requirements by means of the general analysis above. The aforesaid protection should be adequate safeguards for capacitor and condenser during compensation.

Chapter IX

Conclusions and Comparative Analysis

Within the envelope of time from the late 1800's to the present day the synchronous condenser rose to a position of pre-eminence in its own field and only in the last ten years has let slide some of its glory to static capacitors. Cost have been the main factor in elevating the relative position of static capacitors. Modern manufacturing processes have lowered the cost per kva for capacitors to about 1/2 the cost per kva for synchronous condensers. The net result now is that static capacitors are preferred wherever they can perform the same tasks as the synchronous condenser. Where smooth voltage control is desired the condenser still exercises a measure of superiority. However, its prestige is waning even here, because in large power systems fairly large blocks of reactive are required to produce any noticeable effect upon voltages. Switched static capacitors would probably suffice if adequate switching facilities were installed. The switch gear tends to flatten the margin in initial cost between statics and condenser somewhat, but static capacitors still evince smaller operating expenses and lower losses. Included in Figs. 43 and 44

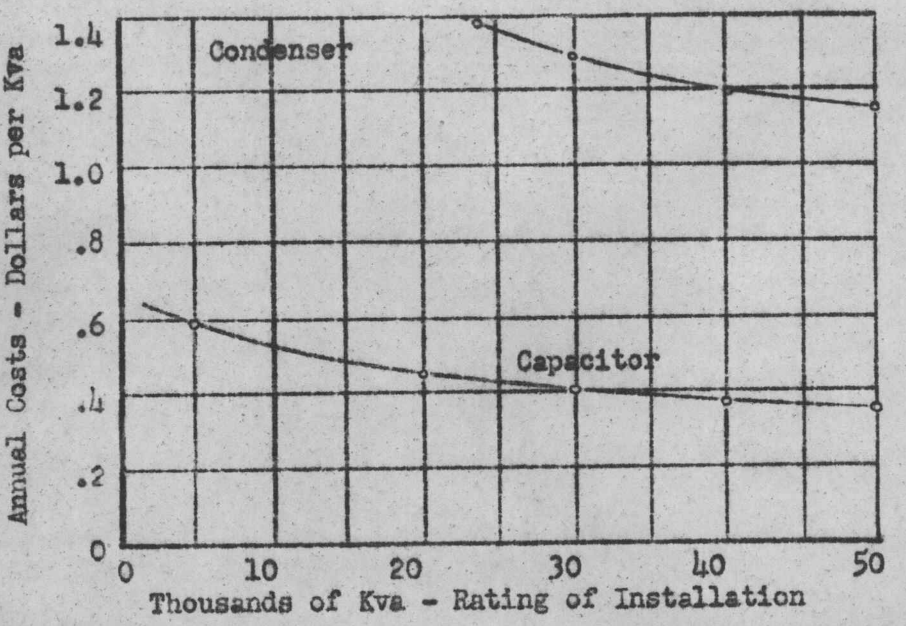


Fig. 43 Annual Costs of Synchronous Condensers and Static Capacitors - Costs Include O&M, Losses, Interest, and Replacement.

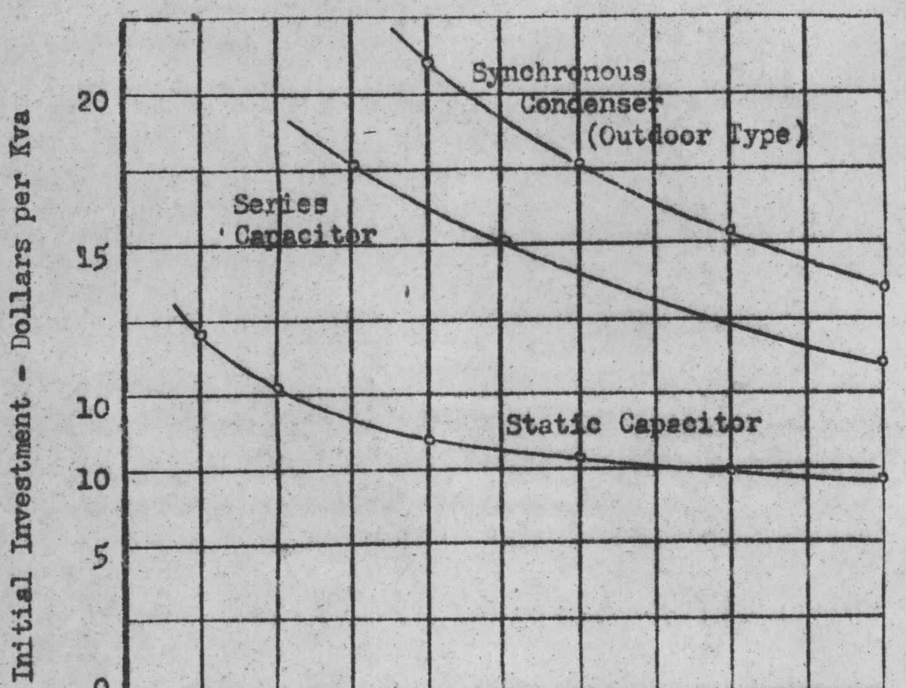


Fig. 44 Initial Installed Cost of Synchronous Condensers and Static Capacitors.

are several cost curves for reference. They were prepared and loaned by courtesy of the System Engineering Staff, Bonneville Power Administration.

As a synchronizing force at major points of inter-tie the condenser does occupy a unique position which capacitors cannot achieve. Earlier we concluded that condensers in the load areas during fault were detrimental to stability and that almost any support to voltages during the fault was injurious, no matter the location. However, with rapid clearing times normal condensers at points of inter-ties are of little consequence to stability. Immediately following the fault additional support to voltages at points of inter-tie prove beneficial to stability. Studies have confirmed this point, but also have shown that fast clearing times or reactor bus schemes at the major generating plants exert more influence on transient stability of the system than the increased support to voltages afforded by the injection of excess kvar into the system at one substation immediately after the fault. Whether a compensated condenser adequately increases the system transient stability limit or whether its support to voltages only lowers the maximum angular separation between machine groups is yet a point of contention for further A.C. Board studies to clarify. Of course, the reduction of maximum angular separation improves system stability, but this could be accomplished by switching capacitors from Y to Δ. Furthermore, any other plan which improves system stability deserves careful consideration before walking blindly into the investment for a compensated condenser. To compare the respective financial obligations involved entails many additional aspects. Characteristics of the capacitor and condenser plans are:

Compensated Condenser

1. The condenser provides synchronizing torque and smooth voltage control.
2. The synchronous condenser provides lagging kvar.
3. Undoubtedly several machines at major substations would require compensation to materially improve stability.
4. Synchronous condensers contribute fault current.
5. Compensation imposes considerable strain on the synchronous machine.
6. Additional relaying is required to prevent compensation during abnormally low voltages or when the condenser provides lagging current.

Switched Static Capacitors

1. Good voltage control can be attained on large systems, as long as lagging kvar are not required.
2. Voltages will sag during the fault as desired, but

switching from Y to Δ after the fault immediately boosts voltages.

3. Capacitors provide no synchronizing torque nor lagging kvar.

In view of these facts we are not surprised that modern practise advocates combined utilization of capacitors and synchronous condensers. At a particular bus where profuse kvar are necessary for power-factor correction on transmission lines, statics can be applied more economically to provide the basic requirements, while synchronous capacity would be desirable for voltage control. Size of the system determines in large measure the ratio of static and synchronous capacity to use or whether switched statics would suffice as mentioned previously. Under the arrangement of combined statics and synchronous either the synchronous or statics or both could be equipped to supply excess kvar immediately following the clearing of a fault. The calculations of chapter V demonstrate that either statics or synchronous condenser could deliver large amounts of kvar. Final judgement as to which method to adopt in a particular case would probably involve an economic study. The estimated costs of compensating a condenser and providing switching for capacitors appear on the next page:

Table 5

Initial Cost of a Compensated Condenser

(30 Mva, $x_d' = 40\%$)

Installed Cost

30 Mva Condenser: 30,000 x \$ 17.50............\$525,000

Series Capacitor for 50% Compensation of x_d':

Minimum voltage as determined by stability curve, Fig. 18, of condenser would be E_b = .75 p.u.

$$i_c(\text{max.}) = \frac{E_d' - .75}{x_d' - x_c} = \frac{1.4 - .75}{.4 - .2} = 3.25 \text{ p.u.}$$

Capacitor Rating = 3.25^2x .2/4 = .528 p.u. = 15,81 Mva

15,810 x \$17.50..................................\$276,675

13.8 Kv Oil Circuit Breaker.......................\$13,000

Total.......\$814,675

(Other installation item costs, such as rod-gaps, resistors, relaying, etc., are assumed small or balanced by similar apparatus in the capacitor case.)

Initial Cost of Static Capacitors For Y to Δ Operation

Installed Cost

For i_c= 3.25 on E_b = .75 p.u. voltage requires 3.25 x .75 = 2.44 p.u. of capacitors.

2.44 x 30,000 = 73,125 mva; 73,125 x \$7.70....\$563,063

6 - 13.8 Kv O.C.B.; 6 x \$13,000...............\$78,000

Total........\$641,063

The switching presents a technical problem which probably could be solved best by some sort of double-throw O.C.B. Otherwise, six breakers will be required, three to open the wye and three to close the delta. The relaying will be elaborate here, but it is off-set by the additional relaying required to prevent instability in the case of the condenser.

The calculations show that the static capacitors are less expensive in initial investment; their operating costs are also lower than for the synchronous condenser. Thus, the compensated condenser may occupy an unattractive position economically. In a particular case other conditions and considerations may improve the picture and demonstrate sufficient benefit to nullify the small economic disadvantage of the condenser, as illustrated above.

As intimated earlier in the thesis, the compensated synchronous condenser possesses a certain allure because of its novelty and the paradoxical idea of compensating a device with leading power factor with a capacitor. It has at least two major applications, one of which is to improve system stability, and the other is to reduce flicker voltages. Successful application can be realized in both cases but apparently at an economic disadvantage. In the former case switching of capacitors offers more economic satisfaction and in the latter case a line series capacitor should be carefully investigated with the compensated condenser. The conclusions are not all negative but, rather, are all positive in the sense, that we hope they contribute a little more knowledge and understanding to the engineer's endless quest for truth, fact, and at times, for just an answer.

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Appendix

Part I. Modified Evans and Sels Transmission Line Charts (Determined from the calculated A, B, C, D constants of the transmission line of chapter II.)

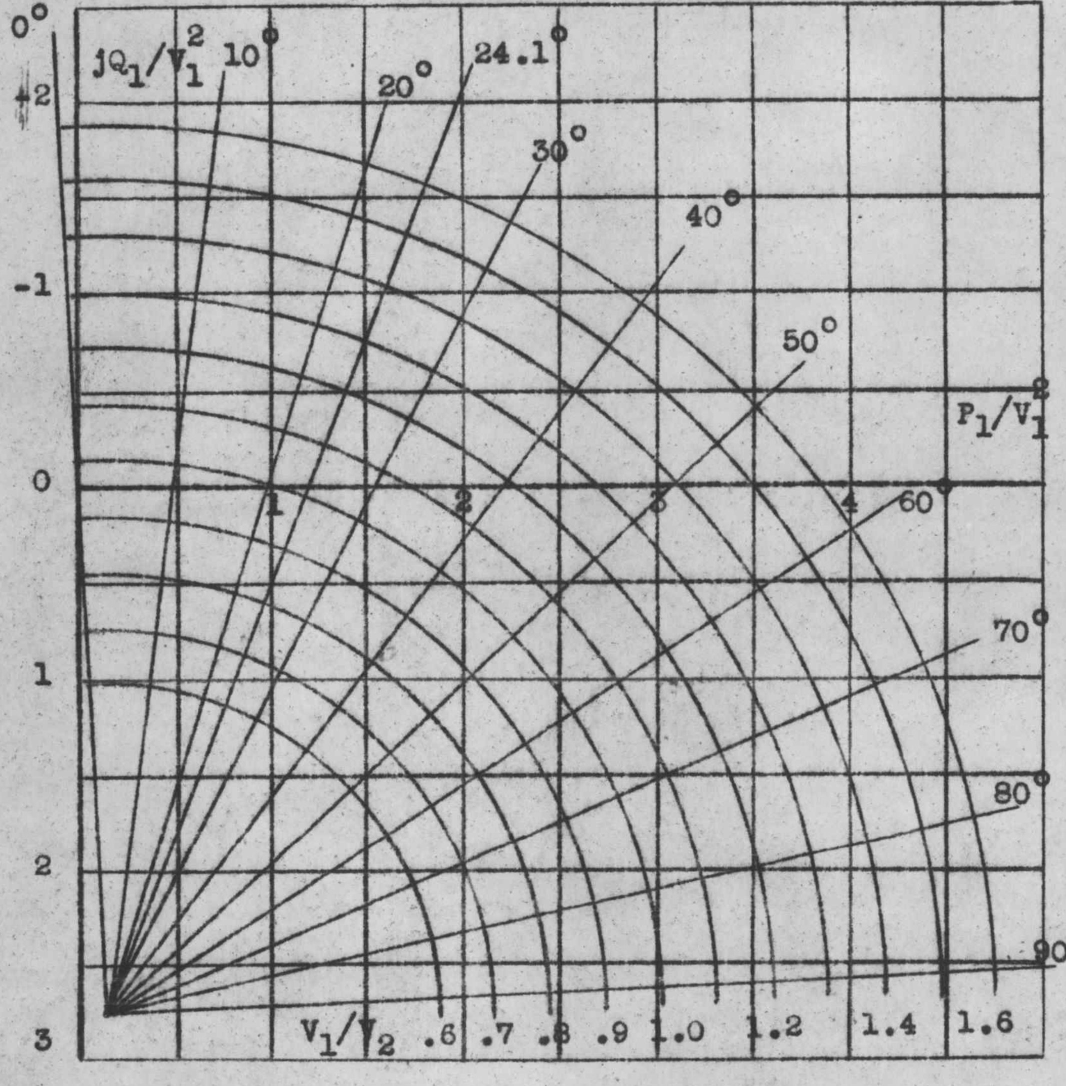


Fig. 45 Generator-End Modified Evans and Sels Transmission Line Chart; Per Unit Quantities.

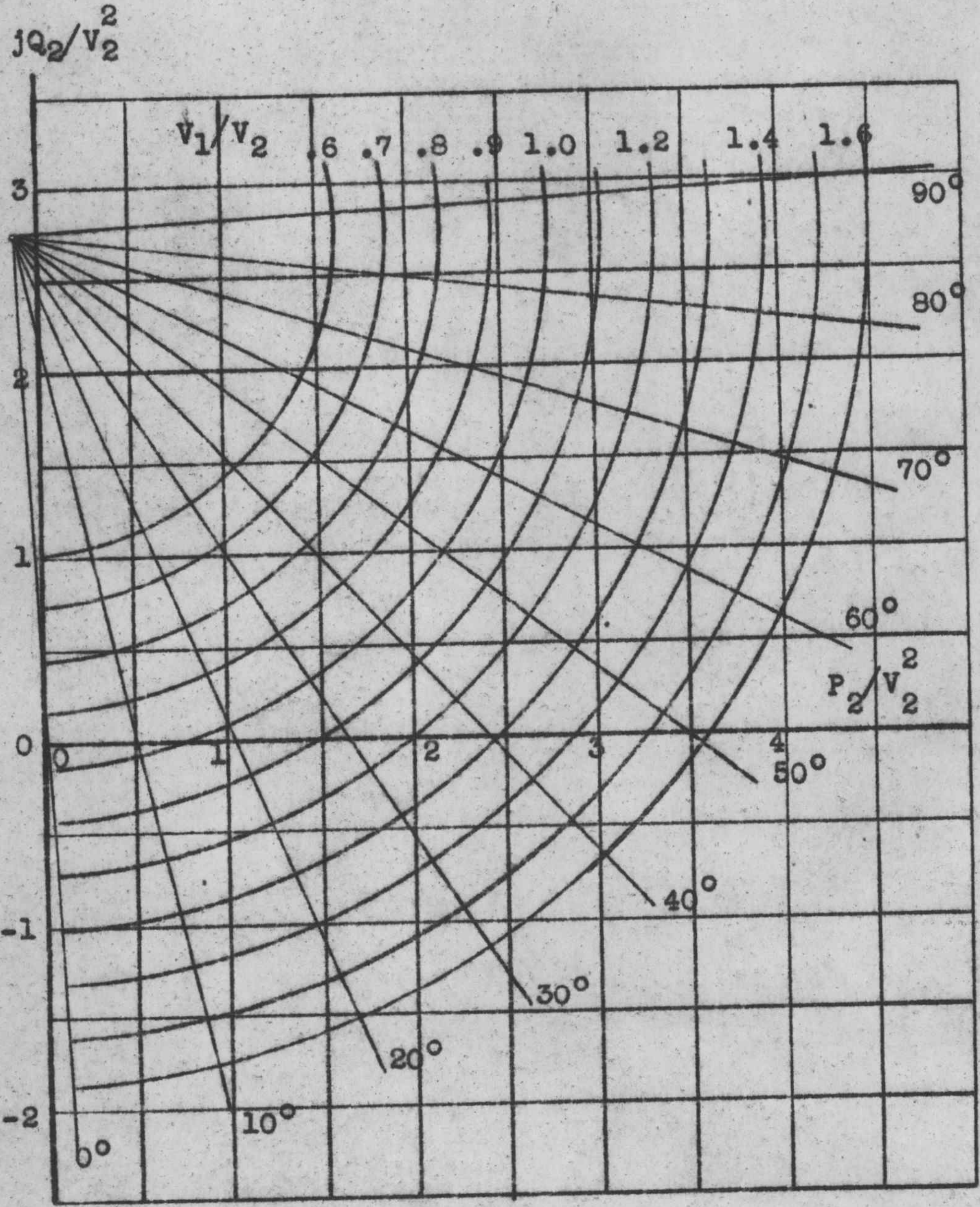


Fig. 46 Load-End Evans and Sels Transmission Line Chart; Per Unit Quantities.

Part II. Determination of Synchronous Machine Constants.

General Electric A.C. Generator
Type ATI 3 Phase 60 Cycle
18.75 Kva .8 P.F. 1200 RPM
Exc. 4.7 Amps. 125 Volts

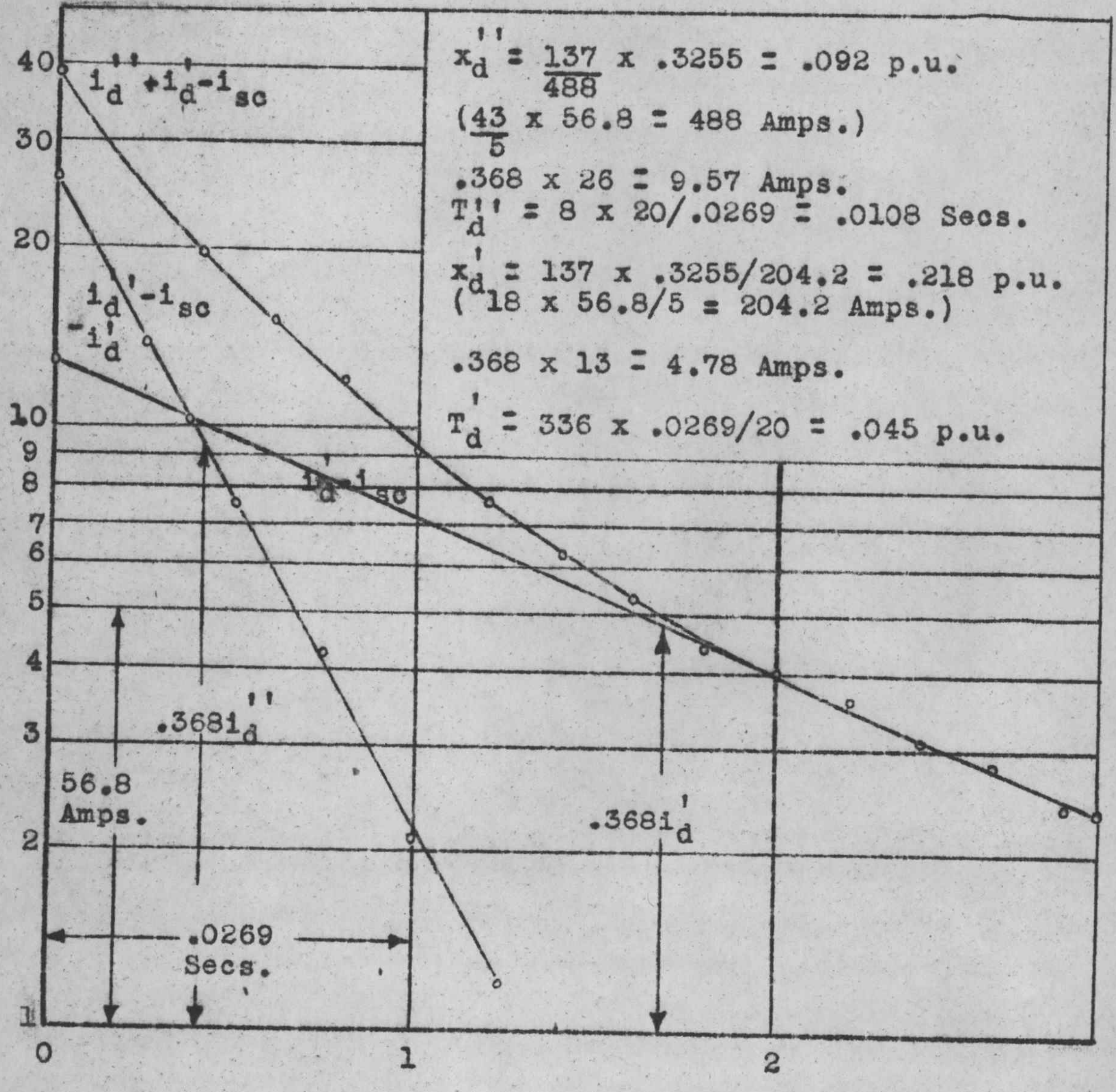


Fig. 47 Typical Calculations From The Following Three Oscillograms For Determination of x_d'', x_d', T_d''; T_d'.
Run #1 - Phase B.
$E_{oc} = 137$ Volts/Phase $I_{sc} = 56.8$ Amperes

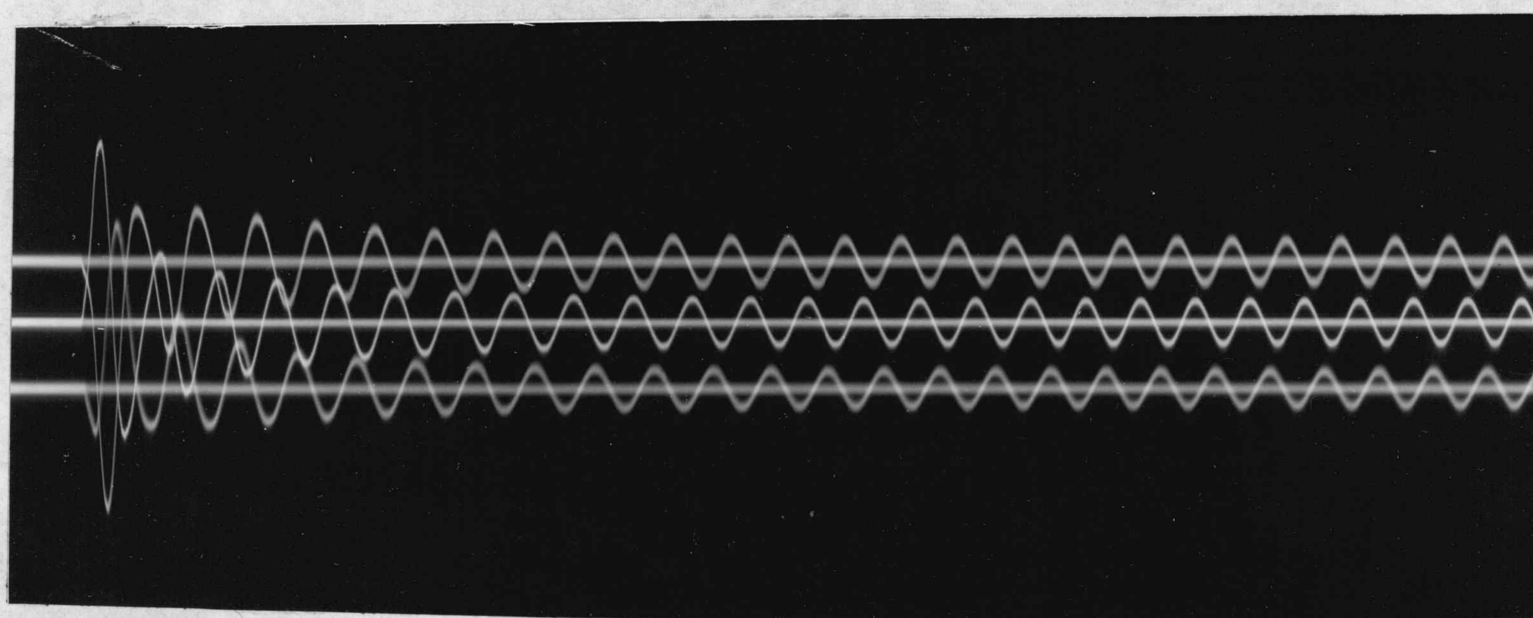
Run #1

3 Phase Short-Circuit

General Electric A.C. Generator
Type ATI 3 Phase 60 Cycle
18.75 Kva .8 P.F. 1200 RPM
Exc. 4.7 Amps. 125 Volts
Ser. No. 5663567

$E_{\text{open circuit}}$ = 137 Volts/Phase

$I_{\text{short circuit}}$ = 56.8 Amps



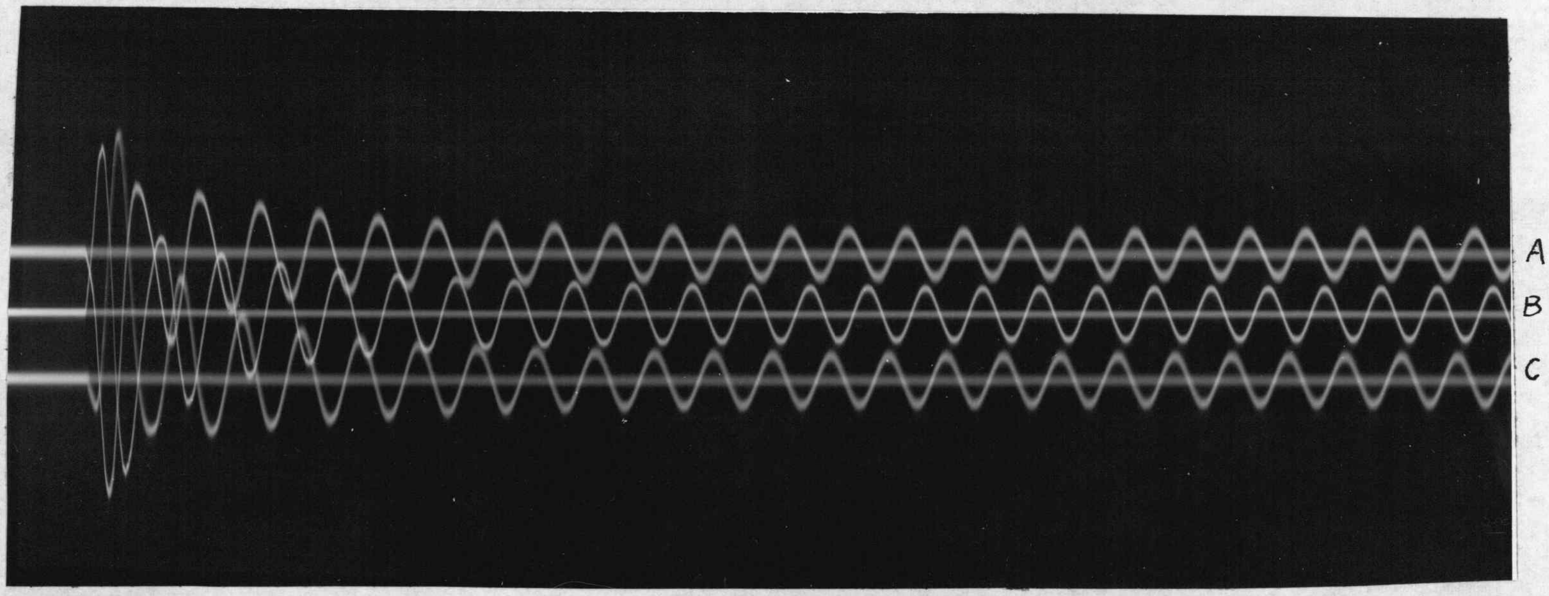
A
B
C

Run #2

3 Phase Short-Circuit

$E_{\text{open circuit}}$ = 136 Volts/Phase

$I_{\text{short circuit}}$ = 56.5 Amperes

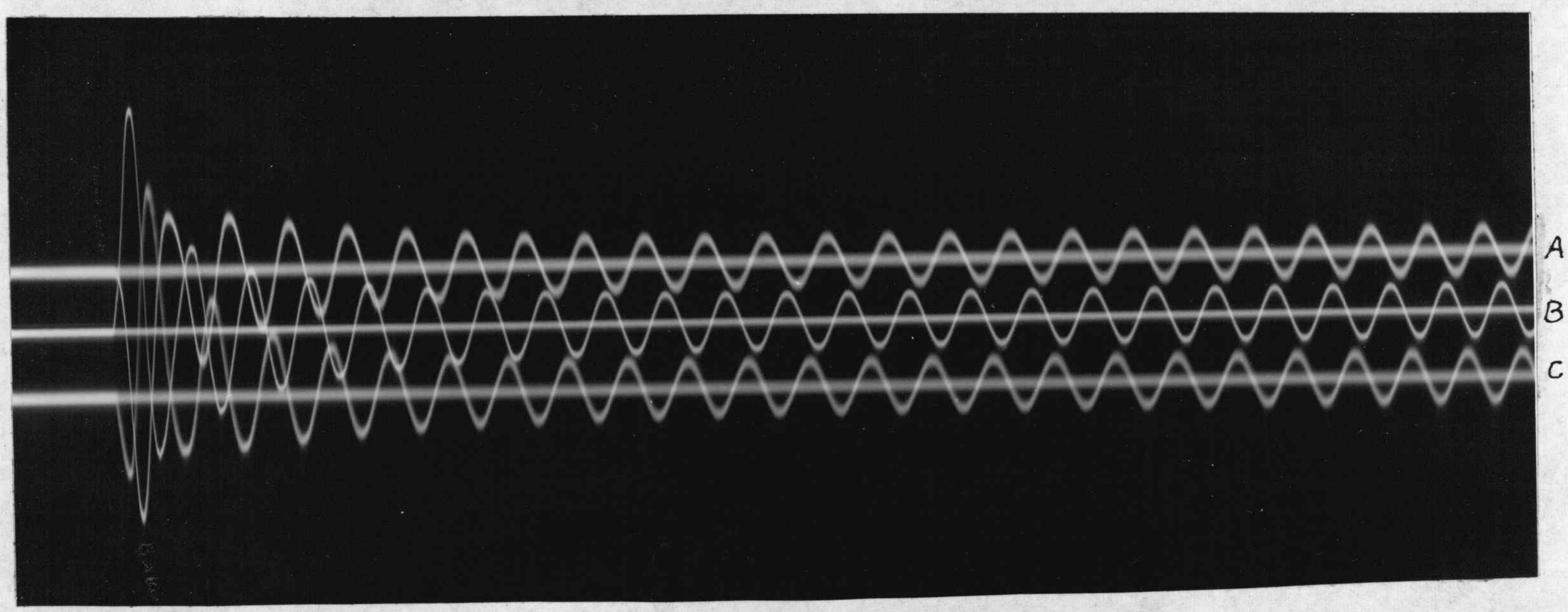


Run #3

3 Phase Short-Circuit

$E_{\text{open circuit}}$ = 136 Volts/Phase

$I_{\text{short circuit}}$ = 56.5 Amperes



Tabulation of Results, Per Unit

18.75 Kva Base

Case	x_d'	x_d''	T_d'	T_d''
1 (A)	.225	.102	.042	.011
1 (B)	.218	.092	.045	.011
2 (B)	.224	.107	.048	.012
3 (B)	.220	.099	.047	.012
Average	.221	.094	.046	.011

(Case refers to run and phase.)

Part III; Proof that A sin wt + B sin Ωt is an amplitude modulated wave.

$$i = A \sin wt + B \sin \Omega t \qquad (a)$$

Let θ be an arbitrary angle, and

$A = k \sin \theta \quad B = k \cos \theta \quad k = \sqrt{A^2 + B^2}$

Substituting in (a),

$$i = k \left[\sin \theta \sin wt + \cos \theta \sin wt\right]$$

$$i = \frac{k}{2}\left[\sin (\Omega t + \theta) + \cos (wt - \theta) + \sin (\Omega t - \theta) + \cos (wt - \theta)\right.$$

Since $\cos \alpha = \sin (90^\circ - \alpha)$,

$$i = \frac{k}{2}\left[\sin (\Omega t + \theta) + \sin \left(\frac{\pi}{2} - wt - \theta\right) + \sin (\Omega t - \theta) + \sin \left(\frac{\pi}{2} - wt + \theta\right)\right]$$

$$i = \frac{k}{2}\left[2 \sin \frac{(\Omega t + \theta + \pi/2 - wt - \theta)}{2} \times \cos \frac{(\Omega t + \theta - \pi/2 + wt - \theta)}{2} + 2 \sin \frac{(\Omega t - \theta + \pi/2 - wt + \theta)}{2} \times \cos \frac{(\Omega t - \theta - \pi/2 + wt - \theta)}{2}\right].$$

$$i = k\left[\sin \frac{(\Omega t - wt + \pi/2)}{2} \cdot \cos \frac{(\Omega t + wt - 2\phi - \pi/2)}{2}\right.$$

$$\left. + \sin \frac{(\Omega t - wt + \pi/2)}{2} \cdot \cos \frac{(\Omega t + wt - 2\phi - \pi/2)}{2}\right] .$$

Regrouping,

$$i = k \sin \frac{(\Omega t - wt + \pi/2)}{2} \left[\cos \frac{(\Omega t + wt + 2\phi - \pi/2)}{2}\right.$$

$$+ \cos \frac{(\Omega t + wt - \pi/2 - 2\phi)}{2} .$$

$$i = k \sin \frac{(\Omega t - wt + \pi/2)}{2} \left[2 \cos \frac{1}{4} (\Omega t + wt + 2\phi - \pi/2\right.$$

$$+ \Omega t + wt - 2\phi - \pi/2) \cdot \cos \frac{1}{4} (\Omega t + wt + 2\phi - \pi/2$$

$$\left. - \Omega t - wt + 2\phi + \pi/2)\right] .$$

$$i = 2k \cos \phi \left[\sin \frac{(\Omega t - wt + \pi/2)}{2} . \cos \frac{(\Omega t + wt - \pi/2)}{2}\right]$$

but, $\sin \left(\frac{\Omega t - wt}{2} + \frac{\pi}{4}\right) = \cos \left(\frac{\Omega t - wt}{2} - \frac{\pi}{4}\right)$

$$i = 2k \cos \phi \left[\cos \left(\frac{\Omega t + wt}{2} - \frac{\pi}{4}\right) . \cos \left(\frac{\Omega t - wt}{2} - \frac{\pi}{4}\right)\right]$$

This is the equation for a modulated wave displaced from the time origin by an angle of 45 degrees.