

LOAD-FREQUENCY CONTROL
OF INTERCONNECTED POWER SYSTEMS

A Thesis
Presented To
The Faculty of Graduate Studies and Research
University of Manitoba

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Electrical Engineering

by
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March, 1962^v



Abstract of Thesis Entitled

LOAD FREQUENCY CONTROL

OF INTERCONNECTED POWER SYSTEMS

A study is carried out into the principal factors involved in the load and frequency control of interconnected power systems. Expressions are developed to give the magnitude of deviation of tie-line power flows and system frequency during times of disturbance in terms of power system and control system parameters. Further expressions are developed to indicate the quality of control likely to be achieved with the given set of parameters.

The results of tests carried out on the load-frequency controls of the Saskatchewan-Manitoba-Northwestern Ontario power interconnection are included and are compared where possible to the theories presented and the expressions developed.

K. H. Williamson,
March, 1962.

PREFACE

The interconnections of power systems evolve in the interests of improved economy, reliability, flexibility and performance. The attainment of these goals is dependent to a large extent upon the performance of the so-called load-frequency or supplementary controls located in the various member areas. The prime function of these controls is to maintain tie-line power flows and system frequency at the scheduled values both during normal operation and during system disturbances. It is desirable, if not mandatory, that these supplementary controls carry out their function rapidly, smoothly and with a minimum of interaction.

The purpose of this study is to assemble and review the principal factors involved in the load-frequency control operation. In the first chapter, the essential parameters involved are defined and expressions are developed in terms of these parameters to give the maximum deviations of system frequency, tie-line power flow and generation imposed by the load-frequency controls as a result of system disturbances. Further expressions, in terms of the same parameters, are developed to indicate the stability tendency of the control systems and controlled generation in the recovery process after system disturbances have occurred. An outline of the more popular supplementary controllers is included.

A description of the design principles of Manitoba Hydro's load-frequency controls is contained in Chapter II as an example of an application of the theories described herein and in the interests of

providing a clearer picture of the test results outlined in Chapter III.

Chapter III contains some of the more pertinent results obtained during the commissioning of Manitoba Hydro's load-frequency controls. Confirmation by these tests of the theories presented and expressions developed is the aim of this chapter.

The author is indebted to the following for their suggestions, comments, contributions and interest in the material presented:-

Professor G.W. Swift of the University of Manitoba, Mr. H. Kaldor of the Saskatchewan Power Corporation, Mr. G.W. Jackson of the Ontario Hydro, and Messrs: L.M. Hovey, L.A. Bateman, E.M. Scott, C.E. Birston, J.T. Atchison and J.G.B. Lliffe, all of Manitoba Hydro. Thanks are also extended to Mr. R. Fleming for much of the draughting involved and to Miss Lorna Jensen who typed the manuscript.

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CHAPTER I

LOAD-FREQUENCY CONTROL THEORY

I - ADVANTAGES OF INTERCONNECTION

The interconnection of power systems creates, in effect, a single larger system with the greater economies, reliability, flexibility, and overall regulation that a larger system implies. In providing a degree of these advantages for itself, the member systems singly would have to provide greater generation reserves.

In a paper presented recently, the principle of interconnection was expanded to apply to Canada as a whole.^{1*} The savings obtained due to the effect of diversity and reduction in reserve capacity amounted to some 2300 mW.** This was based upon the anticipated national capacity requirement in 1965 of some 24,000 mW. The capacity saving, therefore, would be nearly 10%. Another paper, utilizing probability methods, indicates that the capacity savings available to the five member systems due to their mutual interconnection amounted to between 6 and 25%.²

In 1956, Manitoba Hydro (MH) and the Northwestern Region of the Hydro Electric Power Commission of Ontario (HEPCO) interconnected their respective systems by means of an existing 83 mile, 138 kV, single circuit tie-line. Three years later, a 170 mile, 230 kV line, to be operated

*Raised numerals designate references contained in the Bibliography on Pages 79-81.

**See Appendix A on Pages 69-71 for the definition of abbreviations and terms.



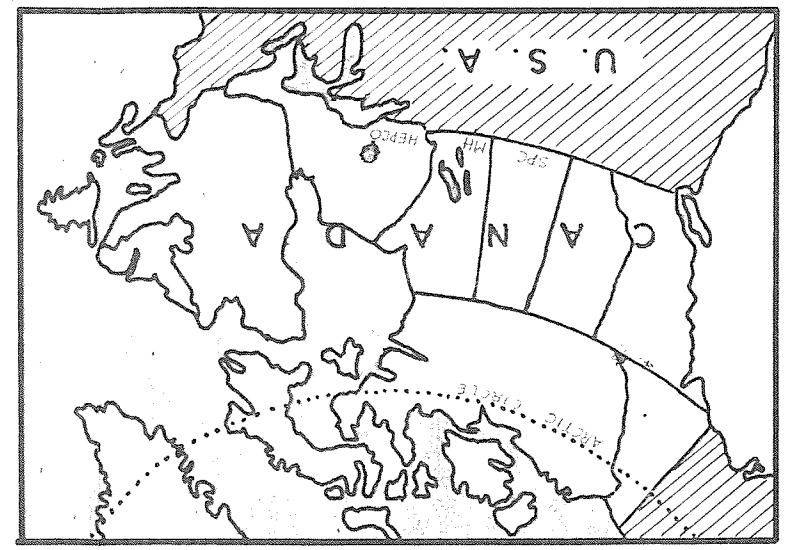
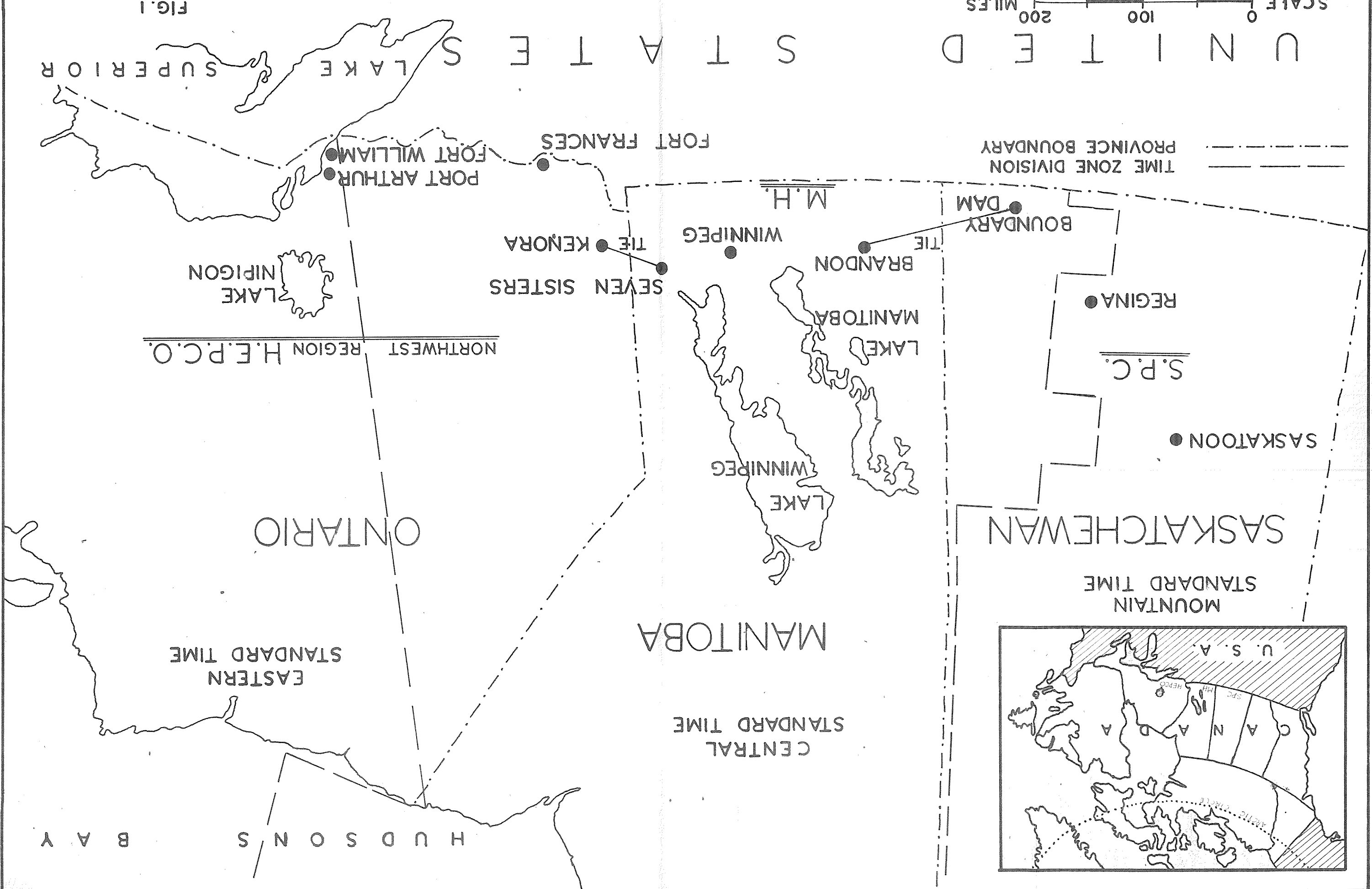
FIG. 1

SCALE 0 100 200 MILES

UNITED STATES

FIG. 1

TIME ZONE DIVISION
PROVINCE BOUNDARY



NORTHWEST REGION H.E.P.C.O.

ONTARIO

EASTERN STANDARD TIME

Hudson's Bay

MANITOBA

CENTRAL STANDARD TIME

SASKATCHEWAN

MOUNTAIN STANDARD TIME

S.P.C.

SASKATOON

REGINA

M.H.

BOUNDARY DAM

BRANDON

MANITOBA

WINNIPEG

SEVEN SISTERS

TIE KENORA

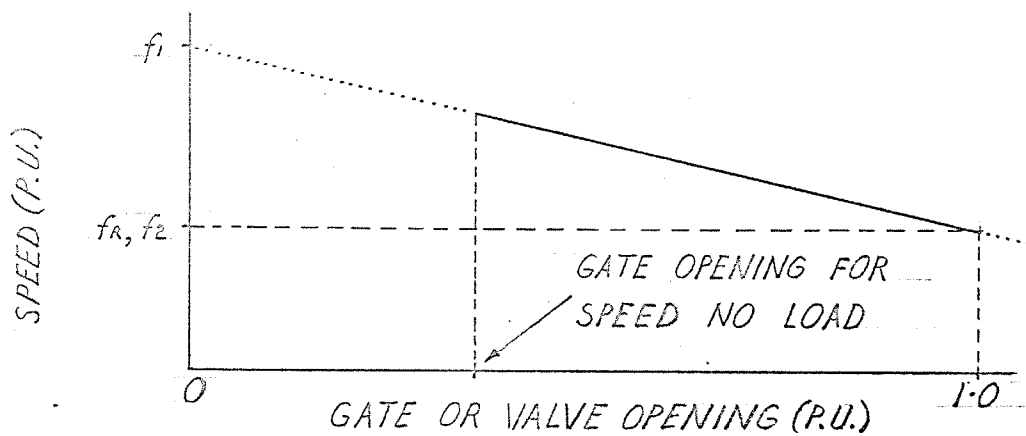
LAKE NIPIGON

PORT ARTHUR

FORT FRANCES

FORT WILLIAM

LAKE SUPERIOR

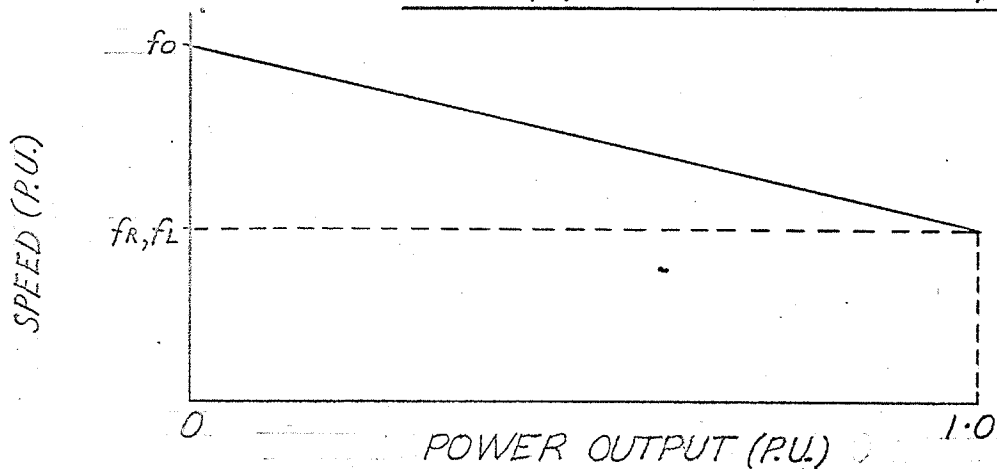


$$G_D = \text{SPEED DROOP} = \frac{(f_1 - f_2)}{f_R} \text{ P.U.}$$

WHERE: f_1 = P.U. EXTRAPOLATED
SPEED CORRESPONDING TO 0%
GATE OR VALVE OPENING

f_2 = P.U. EXTRAPOLATED
SPEED CORRESPONDING TO 100%
GATE OR VALVE OPENING

FIG 2 (a) GOVERNOR SPEED DROOP



$$\text{STEADY-STATE SPEED REGULATION} = \frac{(f_0 - f_L)}{f_R} \text{ P.U.} = G_S$$

WHERE: f_0 = P.U. SPEED OF GENERATOR AT
ZERO POWER OUTPUT

f_L = P.U. SPEED OF GENERATOR AT
1.0 P.U. POWER OUTPUT

f_R = RATED SPEED = 1.0 P.U.

FIG 2 (b) GOVERNOR STEADY-STATE SPEED REGULATION

initially at 138 kV, was completed in 1960 to interconnect the networks of the Saskatchewan Power Corporation (SPC) and (MH). Figure 1 shows the vast area embraced by this three system interconnection. Three time zones are involved and this fact emphasizes the very real advantage of capacity sharing or availability during the time-displaced load peaks within this interconnected area.

II - THE IMPORTANCE OF GOVERNOR SPEED DROOP

Because the action of load-frequency controls is applied to the governing systems of generator units in the form of supplementary control, an outline of power system generation/frequency characteristics brought about by governor action follows.

Figure 2(a) shows the relationship between generator speed and steam valve (thermal unit) or wicket gate (hydraulic unit) opening produced by an ideal governor, i.e. a governor which produces a linear characteristic and has no dead-band with respect to its sensitivity to frequency changes and consequent output change follow up. The reason for the drooping characteristic, which is normally employed, will become apparent presently.

Speed Droop is defined as the overall change in sustained speed, expressed in p.u. (where rated speed = 1.0 p.u.), corresponding to full gate (valve) travel from 0 p.u. to 1.0 p.u. gate (valve) opening with identical setting of all governor adjustments.³

$$\text{Speed Droop, } G_D = \frac{(f_1 - f_2)}{f_R} \text{ p.u.} \text{ ----- (1)}$$

where f_1 = p.u. extrapolated speed corresponding to 0 p.u. gate (valve) opening

f_2 = p.u. extrapolated speed corresponding to 1.0 p.u. gate (valve) opening

f_R = Rated speed = 1.0 p.u. (60 c/s)

Figure 2(b) shows the relationship between generator speed and generator power output produced by an ideal governor.

Steady-State Speed Regulation is defined as the overall change in sustained speed expressed in p.u. (where rated speed = 1.0 p.u.), when the gate (valve) opening of the turbine is reduced from the gate (valve) opening corresponding to 1.0 p.u. power output of the turbine (at rated head, or rated steam conditions) to the gate (valve) opening corresponding to 0 p.u. output of the turbine (at rated head, or rated steam conditions) with identical settings of all governor adjustments.³

$$\text{Steady-State speed regulation, } G_S = \frac{f_0 - f_L}{f_R} \text{ p.u.} \quad \text{----- (2)}$$

where f_0 = p.u. speed at 0 p.u. power output.

f_L = p.u. speed at 1.0 p.u. power output.

f_R = Rated speed = 1.0 p.u. (60 c/s)

Speed droop as defined above should be more correctly termed "Permanent" speed droop in order to avoid confusion with "Temporary" speed droop which has to do with compensation of the governor action. It will be apparent that steady-state speed regulation is directly related to permanent speed droop so that a desired speed regulation is provided by an appropriate permanent speed droop setting. In much of

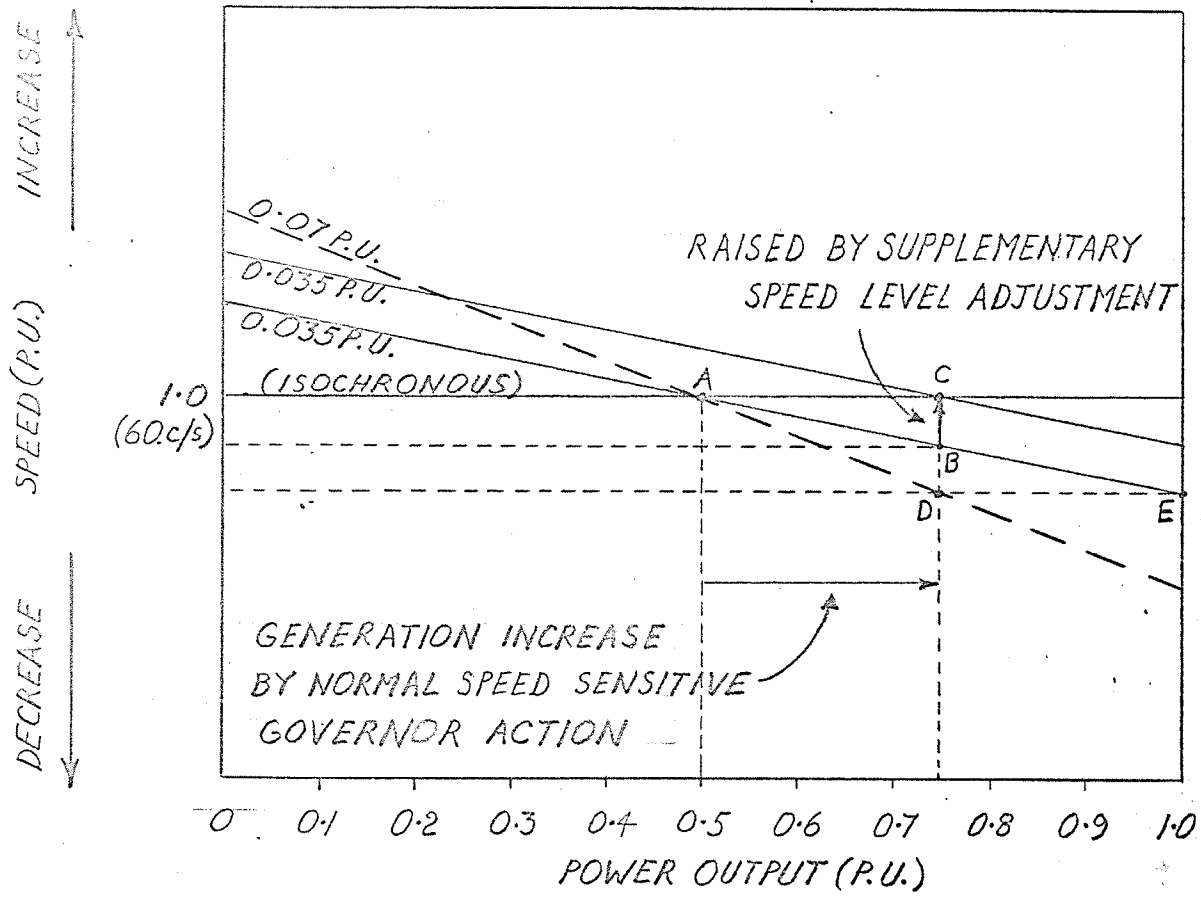


FIG 3 GOVERNOR SPEED REGULATION

the literature on load-frequency controls, steady-state speed regulation is incorrectly referred to as speed droop.

If two units were now considered to be operated in parallel with isochronous (flat frequency) governor characteristics, it would be impossible to load the units according to their capabilities. The division of power between the two units would be unpredictable. For this reason it is necessary to provide the governors of the paralleled machines with drooping generation/frequency characteristics. It must first be realized that for a 60 c/s system (1.0 p.u. speed), generation is considered to balance demand at a speed of 60 c/s only. Deviation from 1.0 p.u. speed, then, is a measure of the excess or deficiency of generation on a system at a given moment. If two identical units are operated alone to supply a connected load and are equipped with governors on .035 p.u. steady-state speed regulation characteristics (See Fig. 3), they will share any load changes equally. If both units are operating at Point A (0.5 p.u. power output) and a load increase depresses the frequency thereby causing operation at Point B, both units will have their power output raised to 0.75 p.u. respectively. Supplementary speed level adjustment to the governor would then be required to bring the frequency back to 1.0 for the new system loading, i.e. Point C.

If one unit were to be operated on 0.07 p.u. speed regulation and the other on 0.035 p.u., it is seen from Figure 3 that the unit on 0.07 would take one-third of the load increase (or decrease) while the one on 0.035 p.u. would take two-thirds. Points D & E in Figure 3 illustrate participation according to the values of percent speed regulation. Participation of a unit in system regulation can therefore be assigned according to this value; the greater the setting, the

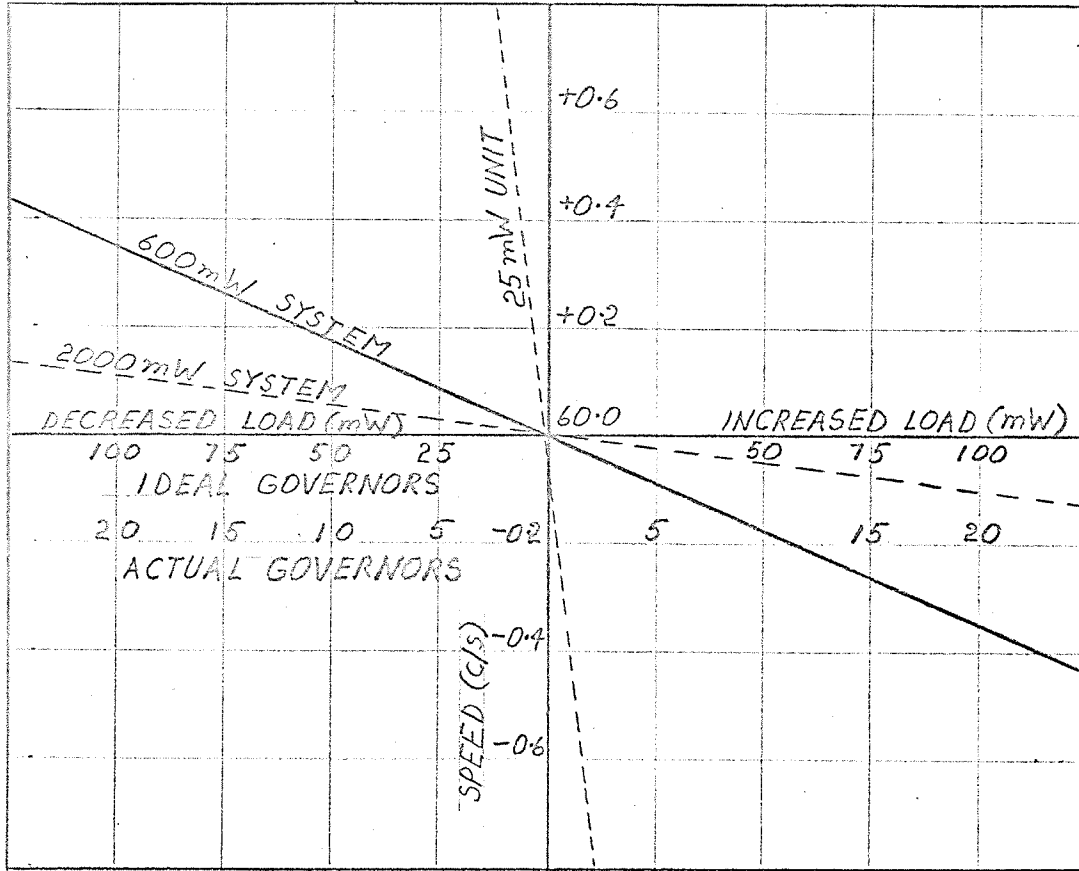


FIG 4. GOVERNING CHARACTERISTICS

(0.035 P.U. STEADY-STATE SPEED REGULATION. SETTINGS USED IN ALL CASES AND A SYNCHRONOUS LOAD IS ASSUMED)