Variation of control characteristics of power thyratron tubes with frequency
by H W Snyder

A THESIS Submitted to the Graduate committee In partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
Montana State University


Abstract:
A study was made of the variation in the control characteristics of three electrode thyratron tubes operation at frequencies up to 1080 cycles per second. Tests were made on thyratron tubes in half-wave rectification with magnitude d-c grid voltage control. The existence of two control characteristics, a starting control characteristic and an extinguishing control characteristic, at higher-than-power frequencies was confirmed. The starting control characteristic was determined to be dependent uoon frequency of spoiled anode voltage, lnterolectrode capacitance, and tube "dark" currents which are determined by geometry of electrode structures. Extinguishing control characteristic was found to be a tube deionization phenomenon.

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# VARIATION OF CONTROL CHARACTERISTICS OF POWER THYRATRON TUBES WITH FREQUENCY

## INTRODUCTION

The industrial application of electric power at frequencies other than those normally employed for generation is increasing rapidly, especially for such specialized purposes as heating, brazing, soldering and melting of metals by induction, speed control of motors by frequency variation, servo-mechanism controls, radar modulators, and aircraft rectifiers and inverters. Power at the desired frequency of utilization is generally obtained from standard frequency power systems by means of frequency converting devices or generating devices which are more and more taking the form of circuits incorporating thyratron tubes. Generally the circuits used in these frequency converting or generating devices are well understood, but until recently the variations which might occur in the control characteristics of the thyratron tubes when subjected to higher-than-power frequencies were not known, though it was and is generally accepted that there are frequency limitations in the use of these tubes because of finite ionization and deionization times.

## HISTORICAL SURVEY

As early as 1934 Berkey and Haller pointed out that thyratron firing characteristics would depend on frequency of applied voltage. It was indicated by W. G. Shepherd[1] in 1943 that there were two control characteristics in thyratron control phenomena which he classed as static and dynamic characteristics. H. H. Wittenberg[2] in 1946 introduced the concept of a starting control characteristic, meaning first cycle starting as compared to successive cycle firing, and an extinguishing control characteristic, meaning failure to ignite on successive cycles, and showed that though these characteristics are generally coincident at low frequencies (60 cycles per second) they may become separate, at least for the control type thyratron tubes, in the audio range of frequencies. As the frequency is increased both control characteristics exhibit shifts, the extinguishing characteristic generally shifting most. It was pointed out that the starting characteristic would tend to shift in a negative direction because of coupling to the grid through the anode-grid capacitance and also because of increased gas pressure, while the extinguishing characteristic would also tend to shift negatively with increase in grid resistance, increase of anode current, increase in gas pressure, the presence of and the amount of inductance in the anode circuit, as well as increasing frequency. It was also noted that the shift was more noticeable in those tubes with larger cross-sectional electrode area (or greater volume).

It was the purpose of this investigation to study the variation in the control characteristics of the larger power thyratron tubes of the single grid, mercury-vapor type because of the trend toward installations requiring more power than control type thyratron tubes can supply. One thyratron tube of the Mercury-vapor-inert-gas stabilized type was also tested. Tubes tested were FG-27A, FG-57, FG-67, 3C23, 967, UX973.

## DESCRIPTION OF TEST EQUIPMENT AND PROCEDURE

Figure 1 shows a diagram of the circuit used for testing the tubes. The taps on the inverter provided adjustable anode voltage for the tube under test up to peak values of 850 volts. $R_L$ was a variable resistor in the anode lead to limit the average anode current. Filament power was supplied from a 60 cycle per second source through a variac in order to keep the filament voltage constant as well as to provide some measure of control of the condensed mercury temperature of the tube under test. A small air blower was also used in this connection.

A sine wave of test voltage was used because wave shape does affect thyratron performance, and the sine wave not only gives results easier to analyze but is also most widely used of all wave shapes. Voltage wave shape was monitored by the cathode ray oscilloscope and checked by comparison of the readings of a rectifier type voltmeter and a radial vane type voltmeter. Frequency of the applied voltage was determined by means of the audio frequency oscillator and the Lissajous pattern on the screen of the cathode ray oscilloscope. Grid voltage was obtained from a 24 volt battery and the potentiometer. The tube undergoing test was fired at the crest of the anode supply voltage wave by magnitude control of the grid voltage and the firing point was monitored with the cathode ray oscilloscope.

The source of the test voltage was a parallel inverter using a pair of FG-67 thyratron tubes. Output power was limited by the input voltage rating of the inverter transformer and the current rating of the inverter tubes. The inverter was chosen as being best able to supply the required variable frequency, variable voltage power source of good output wave shape. Other means of obtaining variable frequency, variable voltage power were studied[3,4,5,] but rejected as being too costly or of insufficient frequency range.

## TEST RESULTS

### STARTING CHARACTERISTICS

It was apparent as testing advanced that the two control characteristics found for the smaller tubes would generally be found for the larger tubes also. The starting characteristics would in general shift with the frequency of the applied anode voltage as can be readily seen in figures 2, 3, and 4, though the degree of shift might be so slight as to be masked by experimental inaccuracies as evidenced by figures 5, 6, and 7 and also by the curve of figure 4 taken at 76° C. condensed mercury temperature.

Figure 3 showing the shift of starting characteristic with frequency in the type FG-67 thyratron tube was of especial interest, since the shift here is shown in a positive direction where all other tubes exhibited, where noticeable, a shift in the negative direction. Wittenberg, as was noted previously, indicated that the negative shift could largely be accounted for by the voltage induced into the grid circuit through the anode-grid capacitance with other factors such as d-c leakage currents and grid emission also contributing.

Consideration of the equivalent circuit for a single grid thyratron tube in half wave rectifier service with a resistance load, source impedance negligible, leads to the following expression for the voltage induced into the grid circuit through the tube interelectrode capacitances including tube base and socket: (See appendix I.)

$$e_g = j\frac{e_p R_g}{X_2} \qquad (1)$$

This equation is, of course, valid only during non-conduction. Figure 8 shows anode-grid coupling in a thyratron tube (exaggerated for purposes of illustration) as calculated by equation 1. It can be seen from figure 8 that the effect of the voltage induced into the grid circuit by the anode-grid capacitance coupling is to require more negative d-c grid bias to prevent firing, though the necessary increase in bias voltage will be less than the crest value of the induced voltage. Also, the induced voltage will tend to fire the tube somewhat before crest anode voltage is reached.

Because of the unusual behavior of the starting characteristic of the type FG-67 thyratron, peak values of induced grid voltages were calculated by means of equation 1 for all tubes used in this study and also for those tubes used in the Wittenberg study and plots were made to determine the amount of shift in starting control characteristic which would be caused in each case. The results of this work are shown in table I in comparison with the shift in starting control characteristic actually observed.

Table I also lists the anode-grid capacitances including tube base and socket as measured for those tubes tested in this study and also those values listed by Wittenberg in his study. It will be noted that the measured values are all greater than the figures published by tube manufacturers. This is because of the added capacitance from the tube base and sockets.

Examination of table I discloses that of the eleven tubes tested the starting control characteristic of one tube shifted in a positive direction. For four tubes no shift in starting control characteristic was observed, though this is not conclusive since the shift predicted for two of the tubes by consideration of anode-grid coupling is so slight as to be masked by experimental error and in the case of the other two tubes the predicted shift is zero. For the remaining six tubes the observed shift in starting control characteristic is substantially greater than that predicted from consideration of anode-grid coupling. In those instances of negative shift in starting control characteristic greater than predicted by anode-grid coupling a part of the added shift may be caused by d-c leakage currents over the stem press between the cathode and grid

TABLE I

COMPARISON OF CALCULATED* AND OBSERVED SHIFT OF STARTING CONTROL CHARACTERISTICS

| Tube Type | Anode-Grid Capacitance Mmfd | Grid Resistance Ohms | Frequency | Crest Anode Volts | Crest Induced Grid Volts | Calculated Shift Volts | Measured Shift Volts | Difference |
|---|---|---|---|---|---|---|---|---|
| 2D21 ** | 0.25 | 0.1 meg | 3500 | 650 | 0.051 | 0.00 | 0.00 | 0.00 |
| 3D22 ** | 0.45 | " | 3500 | 650 | 0.643 | ---- *** | -0.20 | ---- |
| 2050 | 0.60 | " | 1500 | 1000 | 0.570 | 0.00 | -0.90 | ---- |
| 2051 | 0.60 | " | 3500 | 650 | 0.791 | ---- *** | -1.70 | ---- |
| 884 | 6.40 | " | 700 | 300 | 8.43 | -1.60 | -4.0 | -2.40 |
| FG-27A | 11.0 | 5000 | 1020 | 800 | 0.277 | 0.00 | 0.00 | ---- |
| FG-57 | 11.0 | 2000 | 920 | 650 | 0.0897 | 0.00 | -0.35 | -0.35 |
| FG-67 | 12.0 | 5000 | 1280 | 800 | 0.302 | -0.05 | +0.55 | +0.60 |
| 3C23 | 10.0 | 5000 | 1020 | 800 | 0.265 | -0.05 | -0.20 | -0.215 |
| 967 | 16.0 | 5000 | 1020 | 850 | 0.426 | -0.05 | 0.00 | 0.05 |
| UX973 | 13.0 | 5000 | 1020 | 800 | 0.347 | -0.05 | 0.00 | 0.05 |

* Calculated values were computed from equation 1 and accurate plots of applied anode volts, induced volts, and critical grid voltages.

** Shield grid type thyratrons. All others are single grid type thyratrons.

*** Could not be accurately plotted.

Note: 2D21, 3D22, 2050, 2051, 884, data from Wittenberg's article. All other data from present study.

structures, and, in tubes which have been in use long enough for cathode coating to have been deposited on the grid structure, grid emission may account for a part of the added shift. In the case of the type FG-67 thyratron tube none of the foregoing serves to explain the observed positive shift in starting control characteristic.

It is suggested that the positive shift in the starting characteristic of the FG-67 thyratron may be caused by relatively large "dark" currents[4,6,7] in the grid circuit just prior to firing. "Dark"current, the result of electrons leaving the cathode with sufficient thermal acceleration to reach the grid, is normally a function of cathode temperature, grid potential, and anode potential, and may be almost completely zero at high negative grid potentials with low anode voltage. It is interesting to note from figure 8 that the effect of the induced grid voltage is to nullify the effect of the negative grid bias voltage so that the "dark" current increases in magnitude as the applied anode voltage begins to increase positively and add its effect to that of the induced grid voltage to further increase the magnitude of the "dark" current . Since the direction of flow of this "dark" current is from grid to cathode, a voltage drop is produced in the external grid resistance of such polarity as to prevent the tube from firing.

There is some experimental evidence in support of the foregoing. Attempts were made to measure the magnitude of the grid current in the FG-67 just prior to firing, a rather difficult task, since the large value of grid current flowing after firing may damage the instrument used for measurement of the "dark" current. It was determined that when a voltage with a frequency of 550 cycles per second and crest value of 560 volts was applied to the anode circuit of the tube the average d-c grid current, that is, "dark" current, prior to firing was at least 12 microamperes. This is probably well below the actual value of average grid current flowing at just the instant before firing because considerable caution was exercised for protection of the d-c microammeter used to measure the grid current. Also, the microammeter did not measure peak values of any pulsations which might be present.

"Dark" currents are particularly noticeable in the grid circuits of those thyratron tubes where the grid baffle is effectively interposed in the path of the arc-stream. It can be seen from figure 12 that the type FG-67 thyratron is of such construction as to be in this class. The type 967 and type UX973 also are in this class, though here the grid baffles do not lie so completely in the path of the arc-stream. In the case of these last two types no shift in starting characteristic could be observed experimentally, though a slight shift was predicted by consideration of anode-grid coupling. It seems probable that in these types the grid "dark" current was of sufficient magnitude to just counteract the negative shift caused by anode-grid coupling and other effects.

In the case of such thyratron tube types as the FG-57, figure 12 shows that the hole in the grid baffle is as large as the cathode emission hole and so the grid cannot be said to be "interposed" in the path of the arc-stream. It would be expected that grid "dark" current in this case would be small in magnitude and of negligible importance as far as affect of the starting control characteristic is concerned and such is actually the case, no measureable grid "dark" currents being found for this tube.

Attempts were made to measure leakage currents and leakage resistance values in the tubes under test with completely negative results. As an example; the type FG-57 thyratron would require a cathode-grid leakage current of 175 microamperes to account for the difference between the observed and predicted shift in starting control characteristics. No measureable leakage currents were found with negative grid voltages as great as 24 volts. From this it may be conclude that the effect of leakage currents in shifting the starting control characteristic negatively is as small or smaller than the direct effect of grid voltage induced through anode-grid coupling.

The following theory is offered in explanation of the shift in starting control characteristics of three element thyratron tubes:

In any hot cathode tube a certain number of electrons leave the cathode with sufficient thermal acceleration to reach either the grid baffle or the grid-anode space unless the grid is made sufficiently negative relative to the cathode to repel all these high speed electrons. Those electrons reaching the grid baffle surface find their way back to the cathode by way of the grid circuit and produce the grid "dark" current previously mentioned. Those electrons which pass through the grid holes and reach the grid-anode space produce ionization in this region when the anode is at a positive potential. The positive ions produced in the grid-anode space are attracted to the grid and start forming a positive space charge near the grid which tends to nullify the effect of the negative grid bias and so permit more electrons to enter the grid-anode region to produce greater ionization. Unless the grid is made sufficiently more negative to repel all electrons the tube will ignite.

As the frequency of the applied anode voltage is increased the magnitude of the voltage induced in the grid circuit by anode-grid coupling becomes appreciably large. It was pointed out previously that this induced voltage cannot of itself produce all the observed shift in starting control characteristic. It is so phased, however, as to be particularly effective in reducing the effect of the negative grid bias voltage. This will cause the starting control characteristic to shift strongly in a negative direction in those negative-grid thyratron tubes with a single large opening in the grid baffle because the weakened grid field will permit ionizing electrons to pass through the large hole in the grid baffle and reach the grid-anode space. In those negative-grid thyratron tubes with a medium size hole in the grid baffle some electrons may pass through the hole and others strike the baffle resulting in some ionization in the anode-grid region and at the same time, some "dark" current in the grid circuit. The net result may be a slight negative shift, no shift, or a slight positive shift in the starting control characteristic depending upon the size of the hole in the grid baffle. In those negative-grid thyratron tubes constructed like the FG-67 with a grid baffle consisting of a disk with many small holes the weakening of the grid field by the induced grid voltage will cause the grid "dark" current to increase and so shift the starting control characteristic in a positive direction. The starting control characteristic of all positive-grid thyratron tubes should shift in the positive direction.

According to the above theory an increase in frequency should cause the starting control characteristic of the negative-grid thyratron tubes with single large hole in the grid baffle to shift more negatively. Positive-grid thyratron tubes and those negative-grid thyratron tubes with grid baffles made as a disk with many small holes will exhibit a shift of the starting control characteristic in the positive direction. The shift of starting control characteristic of those negative-grid thyratron tubes with a moderate size single hole in the grid baffle will be indeterminate. Increase of grid resistance should produce the same effect as increase of frequency.

Data was taken for each tube at two different values of condensed mercury temperature in order to determine the effect of temperature on starting control characteristic shift. It was expected that at higher temperature the shift would be more negative, since increased temperature effectively increases the gas pressure. Actually the increase in pressure would be about 8% (See Appendix II) which probably would not noticeably affect results. There is some slight experimental evidence that the shift at the higher values of condensed mercury temperature is less than at the lower values of condensed mercury temperature, but this variation in shift is so very slight that it can be charged to experimental error and so should not be considered as being in any manner conclusive. This was especially true in the case of 3C23 which is the mercury-vapor inert-gas-stabilized tube. Here the experimental determination of the starting characteristic at the higher value of condensed mercury temperature became quite difficult, any slight change in filament voltage being instantly reflected in a change of emission and so of starting characteristic. Indeed, at condensed mercury temperatures of 80° C. and above the starting control characteristic becomes so erratic as to be classed as a random phenomena.

EXTINGUISHING CHARACTERISTICS

It was unfortunate that the extinguishing characteristics could not be fully investigated, but power limitations and the inherent unbalanced load presented to the inverter by the test circuit made complete experimental study of the extinguishing characteristic impossible.

At power frequencies of 60 cycles per second the grid can control the average anode current by controlling the point on the positive voltage wave at which the tube fires. This feature is lost at audio frequencies, for here the residual ionization is such that the grid can provide only on-off control of the anode current, at least when only magnitude d-c control is used on the grids.

Tests were made up to the limit of the test equipment which in general seemed to indicate a negative shift of the extinguishing characteristic. The average anode current of these tests was only 0.1 amperes compared to the rated average anode amperes of from 1.25 amperes to 2.5 amperes and so these results can show little more than a trend. Figure 9 shows the measured shift in extinguishing characteristic at 1000 cycles per second frequency applied anode volts for 0.1 ampere average anode current, resistance load, for the type FG-57. Figure 10 shows the measured shift in extinguishing characteristic for the 3C23 at 0.1 average anode amperes, resistance load. In the case of the FG-57 only 4% of rated average anode current is being passed and yet the extinguishing control characteristic has shifted negatively by 10.9 volts at 600 peak anode volts. Part of this shift may be caused by the inductance of the inverter transformer which, by prolonging anode current flow into the time of negative anode voltage, decreases the time available for tube deionization.

Wittenberg has found that a linear relationship exists between average anode amperes and grid voltage required to extinguish a given tube at a given frequency and peak anode voltage. Expressed as an equation this would be

$$e_g = -(K_1 I + K_2) \qquad (2)$$

where $K_1$ would be a constant depending upon electrode geometry, frequency of applied anode voltage, and gas pressure, and $K_2$ would be the grid voltage intercept. It has been shown[6] that under static conditions tube deionization time may be calculated from the empirical relation

$$t = \frac{0.0012\,p\,I^{0.7}}{e_g^{3/2}\,x} \qquad (3)$$

where p is the gas pressure in dynes per square centimeter, I is the arc current, x is the distance between grid and anode, and $e_g$ is the potential of the grid relative to the surrounding space. Operating on equation 3 algebraically to find the grid potential required to deionize a given electrode structure in a given time for various values of arc current results in equation 4.

$$e_g = KI^{0.467} \qquad (4)$$

Plotting equation 4 will show that beyond a certain point the function seems linear in nature. It is possible that Wittenberg did not investigate low current values and so missed this relationship. The present study included only these low current regions and the curvature is plainly seen in figure 11. Because of limited output power available from the inverter it was impossible to carry the tests to high enough current values to be able to predict grid voltage needed to extinguish the tube when passing rated average anode amperes.

Wittenberg has stated that the shift in extinguishing control characteristic is a deionization phenomena and nothing in these present tests is contradictory of that statement.

A series of calculations was made to determine the effect of transient current and voltage surges on tube deionization. These calculations showed that though respectable peak values of surge voltages would be developed,