SATURATED REACTOR DESIGN IN CONJUNCTION WITH CONSTANT VOLTAGE TRANSFORMERS TO REDUCE VOLTAGE DRIFT CAUSED BY FREQUENCY DRIFT

Hillel Errol Cohen

A Research Report submitted to the Faculty of Engineering, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg 1983

FOREWORD

Constant Voltage Transformers (C.V.T.) rely on a stable mains frequency to supply constant voltage to computers and sophisticated electronic equipment. Silbermann (7) has proposed a C.V.T. incorporating a new core geometry which provides for the separation of the primary and secondary leakage reactances. The output voltage of a C.V.T. is dependent on the secondary leakage reactance and therefore by varying this quantity it is possible to change the output voltage. Incorporating a saturable reactor type winding and a simple closed-loop feedback circuit in the secondary leakage reactance path enables control of the output voltage when the mains frequency is varied.

The statement of the problem, electrical specifications and the operation of the control circuit are introduced in Chapter 1. Chapter 2 describes briefly the differences between the basic C.V.T. using stamped laminations and the C.V.T. comprising the new core geometry. A simplified version of the saturable reactor configuration relating to the new core geometry and the control of the output voltage is dealt with in Chapter 3. A block diagram depicting the closed loop control circuit is discussed in Chapter 4. The results, measurements and photographs which verify the validity of the research work are shown in Chapter 5. Any assumptions made in the text are explained and the various stages of the control circuit are described in the Appendix. Further information may be found in the references.

DECLARATION

I declare that this Research Report is my own unaided work. It is being submitted for the degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been previously submitted for any degree or examination at any other University.

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ACKNOWLEDGEMENTS

I would like to thank the following persons for their assistance in the compilation of this Research Report;

Prof. C.F. Landy, my supervisor, for his constant and invaluable assistance at all stages of the research.

Dr. H. Silbermann for his patience and co-operation in helping me to understand his design.

Mr. T. Gomes for his endless support and encouragement.

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CHAPTER 1

INTRODUCTION

Computers and sophisticated electronic equipment require a stable a.c. power supply with low harmonic content in the output voltage waveshape. Constant voltage transformers (C.V.T.'s) have proved to be a reliable constant voltage power source. The major disadvantage of the C.V.T. is its dependence on a stable mains frequency. It is an accepted norm that the output voltage of a C.V.T. changes by 1,5% for every 1% change in frequency (2,3,6,7). A C.V.T. incorporating a new core geometry has been designed which makes it possible to control the output voltage of the C.V.T. when the frequency changes.

The output voltage of any C.V.T. depends on the volt drop across the secondary leakage reactance. The older models of C.V.T. do not have the capability of separating the leakage reactances. In other words a change in frequency affects both the primary and secondary leakage reactances simultaneously. It is therefore difficult to correct for changes in the output voltage. The new C.V.T. geometry enables the primary and secondary leakage reactances to be separated (7). Adjustment of the secondary leakage reactance causes the output voltage to change without affecting any of the other circuit parameters.

It has been shown (7) that by injecting a direct current into a saturable reactor type winding, which is connected in the secondary leakage reactance path, that variation of the output voltage is achieved. Owing to the fact that the output voltage varies when the mains frequency changes, it is possible to use a simple closed loop, continuous feedback system to control the output voltage simply by adjusting the secondary leakage reactance.

A 500 VA prototype C.V.T. without feedback windings or control circuitry has been constructed and tests have been performed to ensure that the C.V.T. operates within the specifications proposed by Silbermann (7). A laboratory experiment has been designed which establishes the feasibility of controlling the secondary leakage reactance. Variable voltage and frequency has been employed to simulate the conditions under which the controlled C.V.T. is to operate (Chap. 5). Finally, the saturable reactor type windings and the control circuit are incorporated into the new C.V.T. geometry to demonstrate the validity of the proposed research work.

The control circuit is of simple design and operates in the following manner. The circuit monitors the actual output voltage which is varying with frequency and compares it to a reference voltage. The difference between the two voltages provides an error signal which is converted into a direct current. The direct current is injected into the control windings and adjusts the secondary leakage reactance, which changes the output voltage, thus reducing the error signal to zero. The output voltage is therefore held at the required set point (Chap. 4).

In all C.V.T. designs a compromise must be met between stability and distortion. If the stability is good, the distortion is bad and vice-versa. Computers and related products require a stable ac supply, but they are sensitive to the harmonics which flow in the system (18,19,20,21,22). The distortion of the C.V.T. output voltage waveshape is therefore an important parameter. Most manufacturers specify that the total harmonic distortion (T.H.D.) be less than 3% at full load.

The original research proposal called for a stabilised dc output voltage which required a full-wave bridge rectifier on the output voltage terminals. However, it has been realised that the percent T.H.D. can be kept to a minimum and therefore, the decision was taken to concentrate on the ac performance of the device.

The specifications for the C.V.T. with the new geometry without control are;

i) For a mains input voltage variation from +10% to -20% of rated input voltage, the output voltage remains constant to within $\pm$ 2% of rated output voltage, with simultaneous load variation from no-load to full-load at 50Hz and at unity power factor,

ii) The percentage total harmonic distortion of the output voltage waveshape does not exceed 3% at rated input voltage at full-load.

Incorporating the saturable reactor winding and control circuit in the new C.V.T. extends the specification to read;

a) For a mains input voltage variation from +10% to -20% of rated input voltage and for a mains frequency variation of $\pm$4%, the output voltage remains within $\pm$1% of the rated output voltage with simultaneous variations from no-load to full-load at unity power factor,

b) The total harmonic distortion does not exceed 3,5% for the specification stated in a) above, at full-load.

Methods have been devised which achieve a similar performance to the proposed design, but these have disadvantages which are not easily overcome. One technique utilises the periodic discharging of capacitors by firing thyristors or triacs. This technique introduces voltage spikes on the system. Also the $\frac{di}{dt}$ of the discharge currents are large, and have to be controlled, and switching noise is unavoidable (8,9). The problem of the voltage switching spikes is eliminated when using closed-loop, continuous control on the new core geometry (7).

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The advantages of the new C.V.T. geometry include ease of construction, small 'snap' action, low harmonic content in the output voltage waveshape, very good output stability, protection from spikes and transients, inherent current limiting capability, excellent noise suppression and as shown in the project, it is no longer dependent on a stable mains frequency.

CHAPTER 2

THE FEASIBILITY OF CONTROLLING THE SECONDARY LEAKAGE REACTANCE

Constant voltage transformers feature widely in the domain of power supplies for sophisticated electronic equipment. The ferroresonant C.V.T. is found in a variety of applications. Each manufacturer has a different core geometry for the C.V.T., but the basic principles are derived from the patent granted to Joseph Sola in 1939.

For the purpose of comparison, the core structure and operation of the conventional C.V.T. using stamped laminations is described. A discussion of the new C.V.T. geometry is presented and the feasibility of controlling the secondary leakage reactance is established.

2.1 The operation of the conventional constant voltage transformer

The construction of the basic constant voltage transformer is illustrated in Fig. 2.1. It consists of a 3 limb shell. The winding space is separated by magnetic shunts shown as S. The primary winding is separated from the secondary by the magnetic shunts and the device constitutes a high leakage reactance transformer. The electrical circuit consists of three windings. The primary winding L_1, secondary winding L_3 and the compensating or bucking winding, L_2. The compensating winding is connected in series with, and opposed to, the secondary winding (4.6.7).

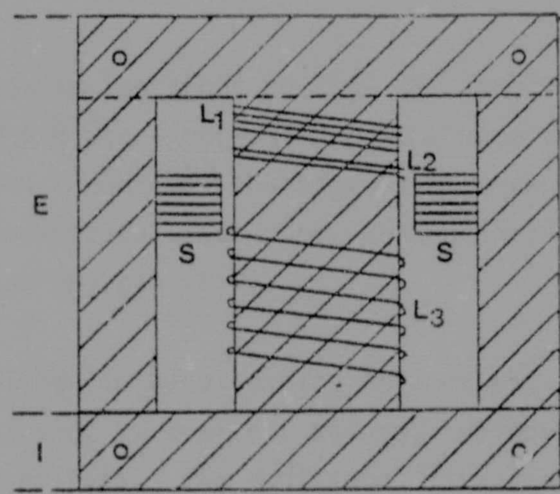


Figure 2.1 Typical core construction of the conventional constant voltage transformer having separate shunts

The connection diagram is given by Fig. 2.2. The capacitor C is connected across the full secondary winding. The capacitor voltage is chosen to be close to the capacitor's rated voltage (440 Vac) which is invariably higher than the required output voltage. Therefore, the capacitor winding is tapped to give the correct voltage. Vin and Vo are the input and output voltages respectively.

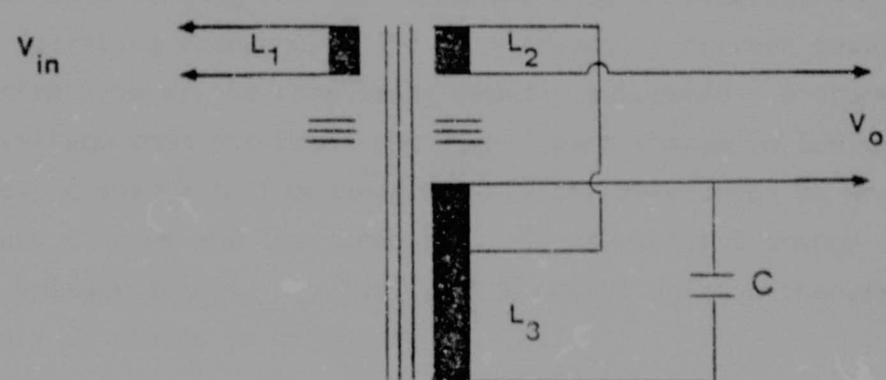


Figure 2.2 Circuit diagram of the conventional C.V.T. of Fig. 2.1

With an increase in the input voltage Vin, the flux density in the centre limb of the core increases and the core tends towards saturation. The inductance therefore decreases and the device moves closer toward electrical resonance. Consequently the voltage across winding L_3 rises sharply (6,7).

The rise in voltage is coupled with an increase in flux linking L_3 but the flux linking L_2 must not change, thereby maintaining a voltage balance on the primary. The additional flux therefore passes through the shunt paths. The primary and secondary leakage reactance has now increased and the total inductance as seen by the capacitor terminals is such that resonance occurs. Any change in the flux density in the primary circuit, through changes in the input voltage, is independent of the flux condition of the secondary circuit as long as the resonant condition of the secondary circuit is maintained.

The voltage across the capacitor C (Fig. 2.2) is greater than the required output voltage Vo. Winding L_3 is therefore tapped at the required number of turns. When the input voltage reduces, the ampere turns in the winding L_3 is reduced, so the bucking winding L_2, in antiphase with winding L_3, is provided to counterbalance this effect (4,6,7).

The secondary winding and the capacitor form a ferroresonant circuit at the operating frequency. The high capacitor current results in the centre limb of the core being heavily saturated. A change in the input voltage does not cause any significant change in the output voltage. A change in frequency affects the reactances of both the secondary winding and the capacitor. Consequently a change in the output voltage occurs. Typically, the output voltage changes by 1,5% for every 1% change in frequency (2,3,6,7).

2.2 Improving the constant voltage transformer

A unique C.V.T. incorporating a 'new' core geometry has been designed (Patent 77/2240 et al) (7). This design allows the primary and secondary leakage reactances to be changed individually. From the physical configuration of Fig. 2.3 it is seen that: "The basic core type structure is associated with the core C_2, with the primary L_1 on the left and the secondary L_2 on the right. Core C_1 forms the primary leakage flux path and has an airgap that is easily varied, thereby allowing the amount of primary leakage flux to be adjusted. Likewise core C_3, which also has an airgap, forms the secondary leakage reactance flux path. The variation of the airgap in core C_3 allows the secondary leakage reactance to be changed and allows for adjustment of the secondary output voltage" (7)

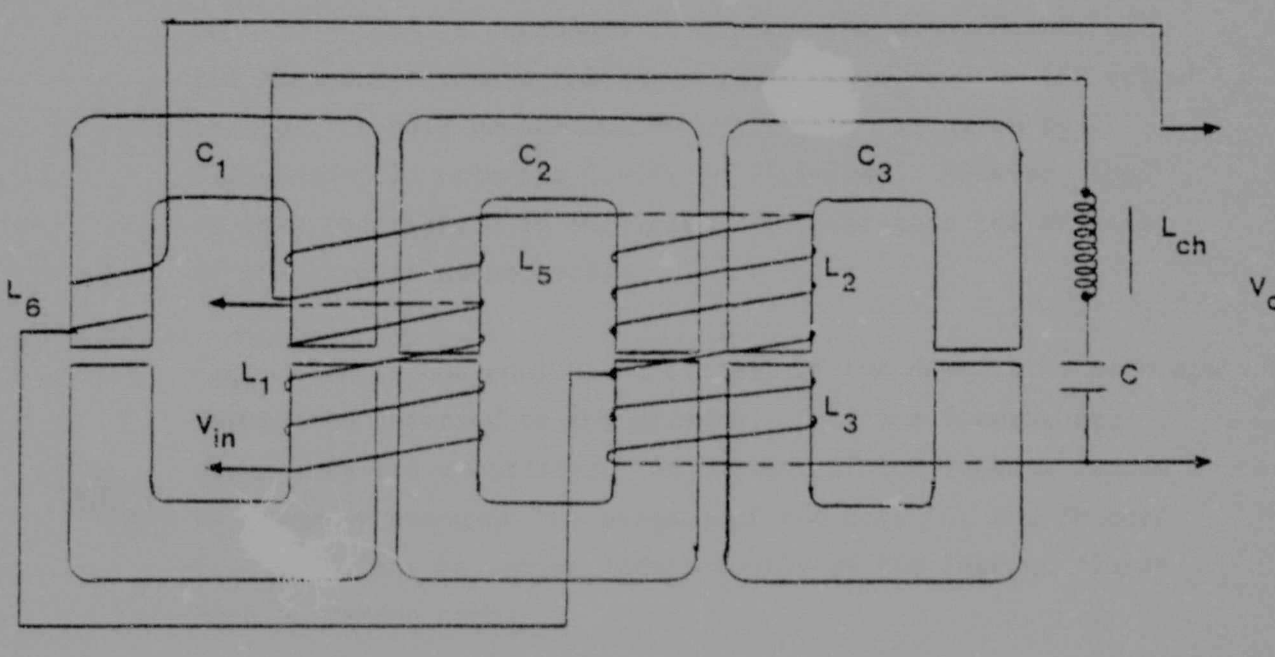


Figure 2.3 Original core/winding arrangement of new constant voltage transformer showing the single core C_3

Use is made of the third harmonic current in the primary circuit to reduce the total harmonic distortion. Winding L_6 is connected in antiphase to the output winding and the third harmonic in the output voltage waveshape is reduced.

By adjusting the airgap length of core C_1, the flux density in the core C_2 can be altered. Adjusting the airgap length of core C_3 causes the voltage drop across the secondary leakage reactance to change. The effect of opening the airgap in core C_3 is that the output voltage decreases due to the reduction of the secondary leakage reactance (7).

2.3 Phasor representation at no-load

A phasor representation of the constant voltage transformer on no - load is necessary to explain the significance of the secondary leakage reactance volt drop effect on the output voltage. A more comprehensive explanation is given by Silbermann (7) with the C.V.T. on full-load. However, the no-load description is sufficient to understand the effects of the circuit parameters.

Fig. 2.4 is the equivalent circuit of the new C.V.T. with all quantities referred to the primary. Only the fundamental components are considered. Adjustment of the leakage fluxes is made by changing the airgaps of the core C_1 and/or core C_3. These may be varied independently as the leakage fluxes have no common path.

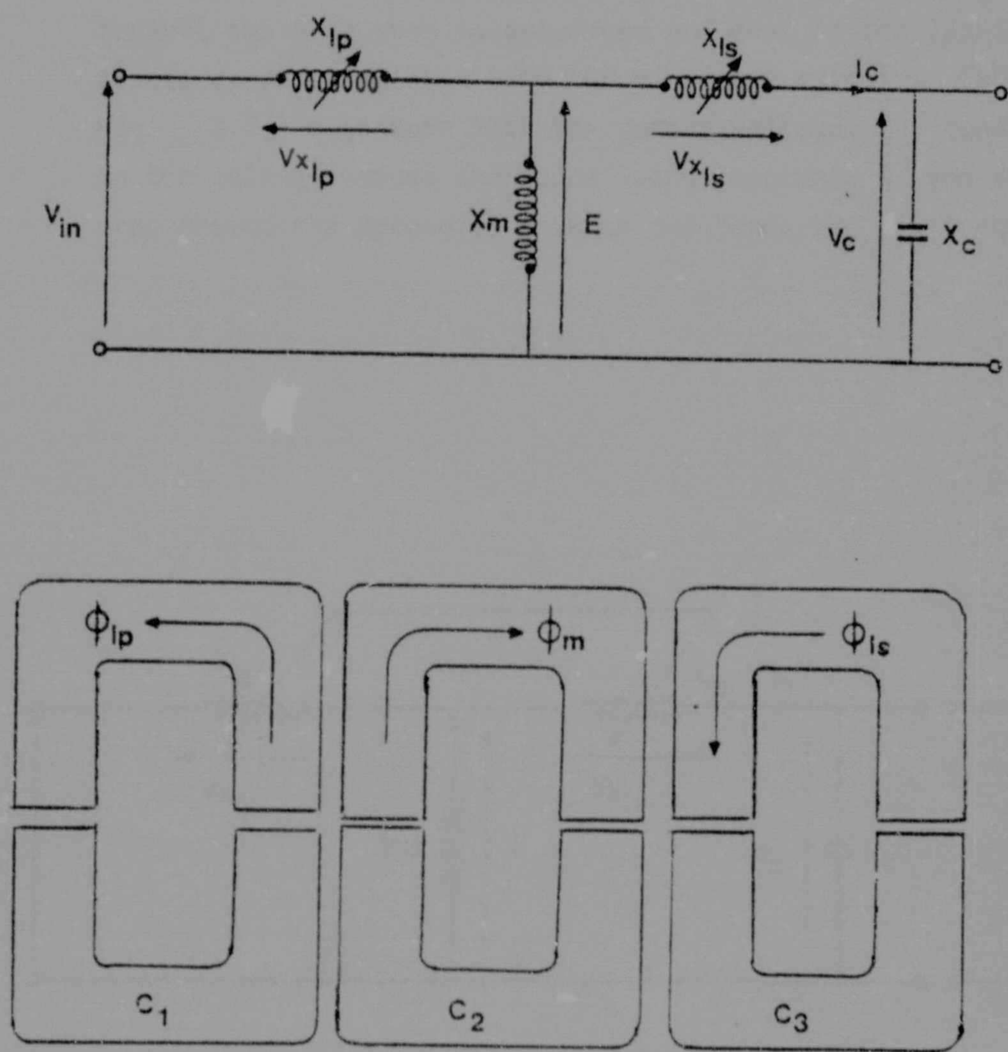


Figure 2.4 Equivalent circuit of the constant voltage transformer on no-load showing the direction of flux in the C-cores

- $\emptyset_m$ is the flux due to the magnetising current
- $\emptyset_{ls}$ is the secondary leakage flux
- $\emptyset_{lp}$ is the primary leakage flux
- X_{lp} is the primary leakage reactance
- X_{ls} is the secondary leakage reactance
- X_m is the magnetising reactance
- X_c is the capacitor reactance

The equivalent circuit for the conventional C.V.T. is shown in Fig. 2.5. Since the C.V.T. is a high leakage reactance transformer, the main core is saturated and most of the leakage reactance is associated with the secondary circuit. From Fig. 2.5, it is seen that the output voltage, Vc, depends on the voltage across the magnetising reactance E and the volt drop across the secondary leakage reactance Vx_{ls} (see equ. 2.5)

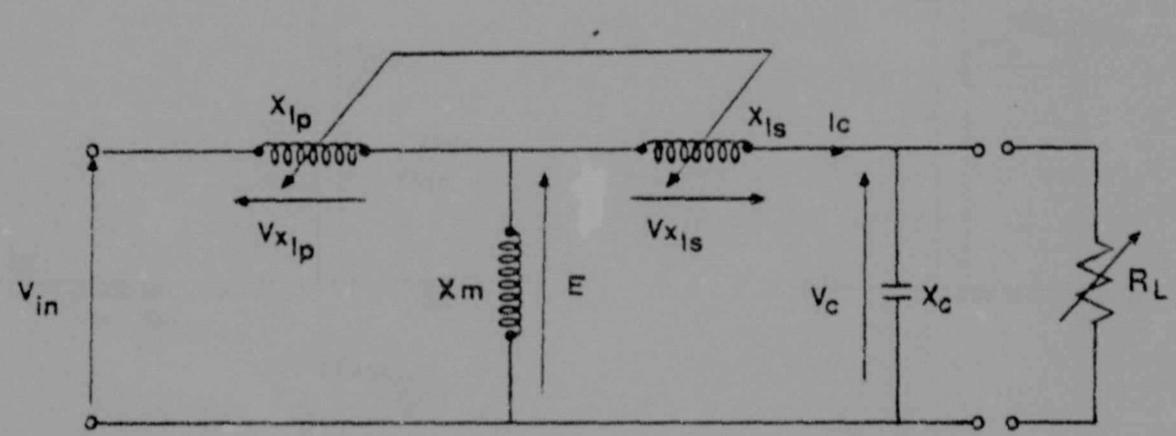


Figure 2.5 Simplified equivalent circuit of the conventional C.V.T. on no - load with all quantities referred to the primary

-X_{lp} is the primary leakage reactance

-X_{ls} is the secondary leakage reactance

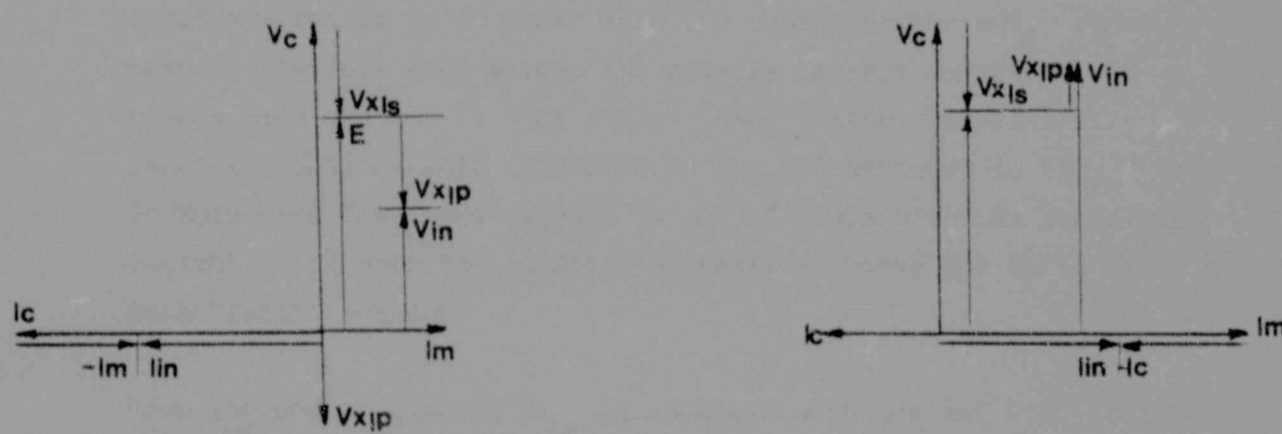
-Xm is the magnetising reactance

-Xc is the capacitor reactance

Separate control of the secondary leakage reactance is impossible to achieve, since the primary and secondary fluxes traverse a common path via the magnetic shunt paths. If the reluctance of the shunts and their airgaps are changed then both the primary and secondary leakage reactances change.

Comparing Figs. 2.4 and 2.5 it is seen that in Fig. 2.4 either the primary and/or the secondary leakage reactance may be changed whilst both the reactances in Fig. 2.5 change simultaneously.

The phasor diagrams of the new C.V.T. are shown below in Fig. 2.6



$Im < Ic$ $\quad$ $Im > Ic$

$Vin = E - Vx_{1p}$ $\quad$ $Vin = E + Vx_{1p}$

a) $\quad$ b)

Figure 2.6 Phasor diagram associated with the circuit of Fig. 2.4 where the emf E is the secondary induced emf referred to the primary.

As already mentioned the transformer core C_2 is driven deep into saturation with flux densities reaching as high as 2,1T. The magnetising reactance $Xm = \frac{E}{Im}$ is non-linear and varies as E varies. A very large magnetising current Im is required to saturate the core. The large current Im is counterbalanced by the capacitor current which results in a small input current.

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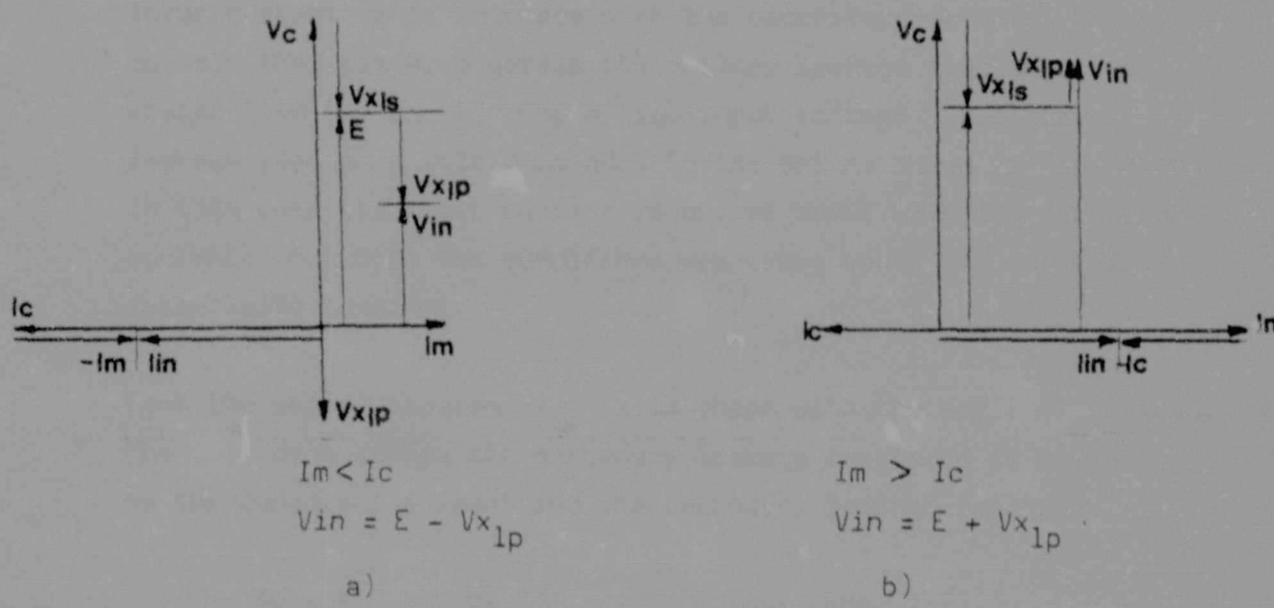

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A change in input voltage causes a change in the input current Iin. Consequently a change in the primary leakage reactance volt drop $I_{in}X_{1p} = Vx_{1p}$ is observed. It has been shown (7) that when Im changes Xm also changes and the product ImXm=E is practically constant. If E is constant then a change in capacitor voltage can only occur if the secondary leakage reactance volt drop Vx_{1s} changes.

From Fig. 2.6 a,b two conditions exist for an input voltage variation. For a low input voltage the magnetising current Im is greater than the capacitor current. Fig. 2.6a shows that for this condition the input current Im is in phase with the capacitor current. Consequently the volt drop across the primary leakage reactance subtracts from the emf E. For a high input voltage the primary leakage reactance volt drop adds to the emf as shown in Fig. 2.6b. In this case the input current is out of phase with the capacitor current. For both the conditions described above the emf E is essentially constant.

From the phasor diagram Vx_{1s} is in phase with the emf E at no-load. The volt drop across the secondary leakage reactance is given by the capacitor current and the secondary leakage reactance.

$$Ic \times X_{1s} = Vx_{1s} \qquad \text{---- (equ. 2.1)}$$

With all quantities referred to the primary the magnitude of Ic is

$$|Ic| = \frac{E}{|Xc - X_{1s}|} \qquad \text{---- (equ 2.2)}$$

For the case where Im < Ic (Fig. 2.6a)

$$Vin = E - Vx_{1p} \qquad \text{---- (equ. 2.3)}$$

OR

$$Vx_{1p} = X_{1p} \text{ (Im - Ic referred)} \quad \text{---- (equ. 2.4)}$$

As Ic decreases, Vx_{1p} increases and E decreases, but from equ. 2.1 if Ic decreases then Vx_{1s} is reduced and consequently E decreases. E and Vx_{1s} have both decreased therefore the output voltage Vc is reduced.

Owing to the fact that the core C_2 is heavily saturated the assumption can be made that E changes very little for a change in input voltage Vin and therefore only Vx_{1s} changes.

$$Vout = Vc = E + Vx_{1s} \quad \text{---- (equ. 2.5)}$$

Therefore if X_{1s} decreases $|Xc - X_{1s}|$ increases by equ. 2.2 and $|Ic|$ decreases. The overall effect is that the output voltage is reduced.

2.4 The Saturable Reactor

The reactance of an iron-cored coil may be varied by introducing a component of mmf having a constant magnitude so that during certain portions of the cycle the net mmf in the core exceeds the saturation value. The constant mmf component is produced by a dc excited coil which links a portion of the magnetic circuit and changes the reluctance of the core for the alternating flux. By varying the direct current in the control windings, the reactance of the ac windings may be adjusted.

The method by which control of the secondary leakage reactance is achieved is by incorporating a saturable reactor type winding on the split C-core C_3 (See Chap. 3 Fig. 3.1). It is necessary to explain the basic properties of a saturable reactor winding in relation to the constant voltage transformer of Figs. 2.3 and 2.5.

The saturable reactor core must have the following properties;

a) very high permeability of low flux densities,
b) a well defined point of saturation,
c) very low permeability at flux densities in the saturated region.

The magnetising curve of the magnetic material may be approximated by three straight lines as shown in Fig. 2.8.

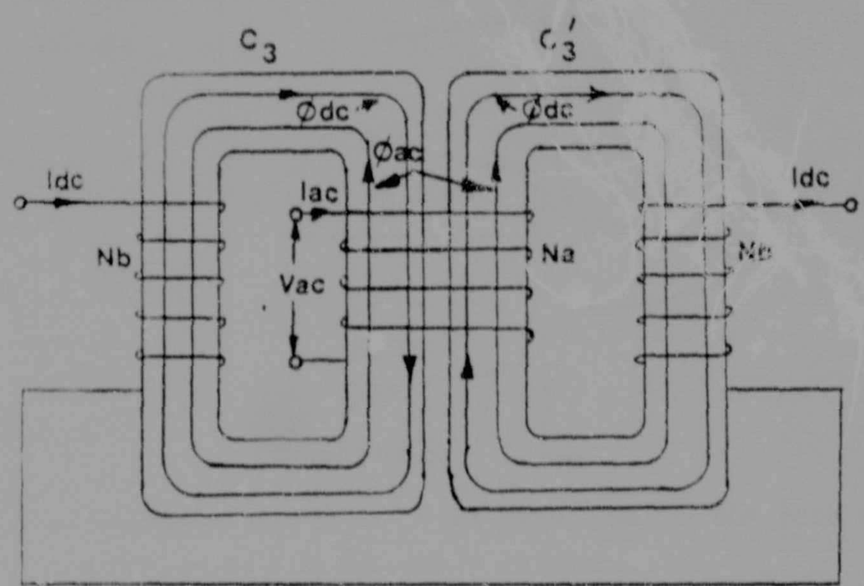

Figure 2.7 Core C_3 Fig. 2.3 split into 2 C-cores C_3 and C_3' with dc winding connected as shown