A GUIDE TO VARIABLE TRANSFORMERS

By

Rudi Kremer

Dipl. Ing.

Vice President – Engineering

Phenix Technologies

PHENIX TECHNOLOGIES
INDUSTRIAL DRIVE, ACCIDENT MD. 21520

April "95"

OUTLINE

A. INTRODUCTION

- Variable Transformers and their application to Voltage Regulation.

B. VARIABLE TRANSFORMER DESIGN & APPLICATION

- Application.
- Types of Variable Voltage-Regulating Transformers.
- Variable Voltage-Regulating Transformers for Research & Testing.

C. VARIABLE TRANSFORMER ELECTRICAL DESCRIPTION

- Autotransformer Principle
- Common Electrical Circuits
- Equivalent Circuit
- Overload Rating and Overload Protection
- Short Circuit Characteristic

D. SUMMARY

APPLICATIONS OF VOLTAGE-REGULATING TRANSFORMERS

- Industry, research institutions, and electric utilities need stepless on-line control of voltage and power.

- This need is currently met primarily with power-electronics based voltage CONVERTERS, INVERTERS, and SOLID-STATE AC REGULATORS operating on phase-control.

- For special applications VARIABLE VOLTAGE-REGULATING TRANSFORMERS are required, especially where smoothly variable voltage is required, as in:

  - Electroplating equipment
  - Electrophoresis coating plants
  - Melting furnaces
  - Telecommunication centers
  - Research laboratories

- VARIABLE VOLTAGE-REGULATING TRANSFORMERS are used wherever the voltage must be smoothly adjusted on-line over a wide range of voltages without impacting the power factor or harmonic content.

- Test and Research Laboratories generally prefer voltage. regulating systems that guarantee *a ratio of peak voltage to RMS voltage = square root of 2* (i.e., pure sinusoidal voltage at the fundamental frequency).

- VARIABLE VOLTAGE-REGULATING TRANSFORMERS can meet this requirement without additional filters.

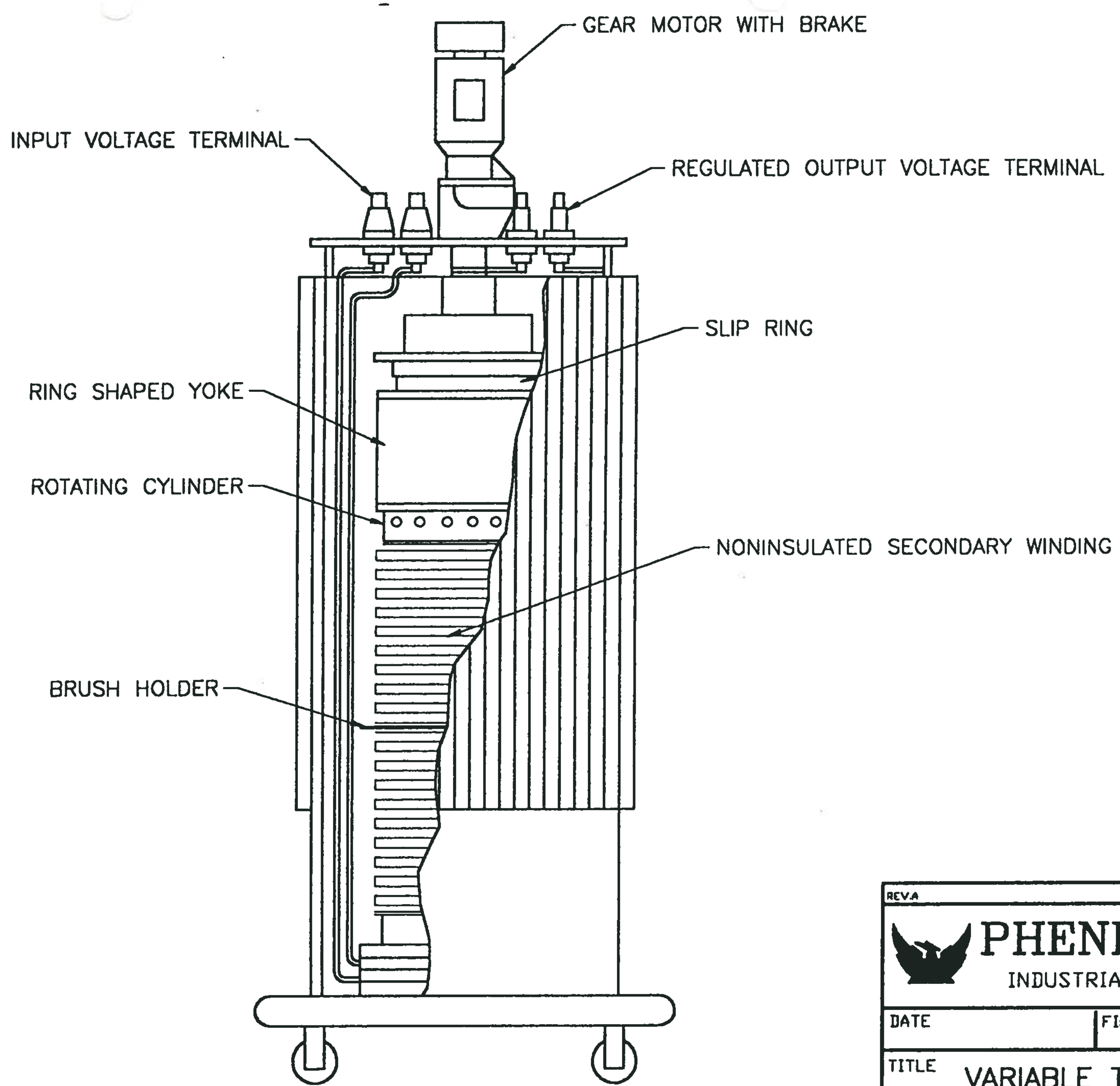
TYPES OF VARIABLE VOLTAGE-REGULATING TRANSFORMERS

- THOMA VARIABLE TRANSFORMERS
- TOROIDAL VARIABLE TRANSFORMERS
- COLUMN-TYPE VARIABLE TRANSFORMERS (CTVT)
- MOVING-COIL VARIABLE TRANSFORMERS

DESIGN AND PERFORMANCE OF THOMA VARIABLE TRANSFORMERS

A THOMA VARIABLE TRANSFORMER is a type of variable transformer in which a single layer of non-insulated wire is wound onto a rotating cylinder. The brush-holder assembly moves axially over the secondary winding, producing a continuous stepless, pure sinusoidal waveform without distortion.

- The short-circuit impedance is constant and relatively low.
- The voltage is adjusted continuously without steps.
- The regulator does not generate electromagnetic interference (EMI).
- Approx. 98% efficient.
- Primary application is for high-power control up to 4000 MVA single phase.
- Input voltage range 1 - 30 kVAC.
- Output voltage range 0.5 - 3 kVAC.
- Lagging power factor.
- Large overload capability relative to the short-circuit impedance.

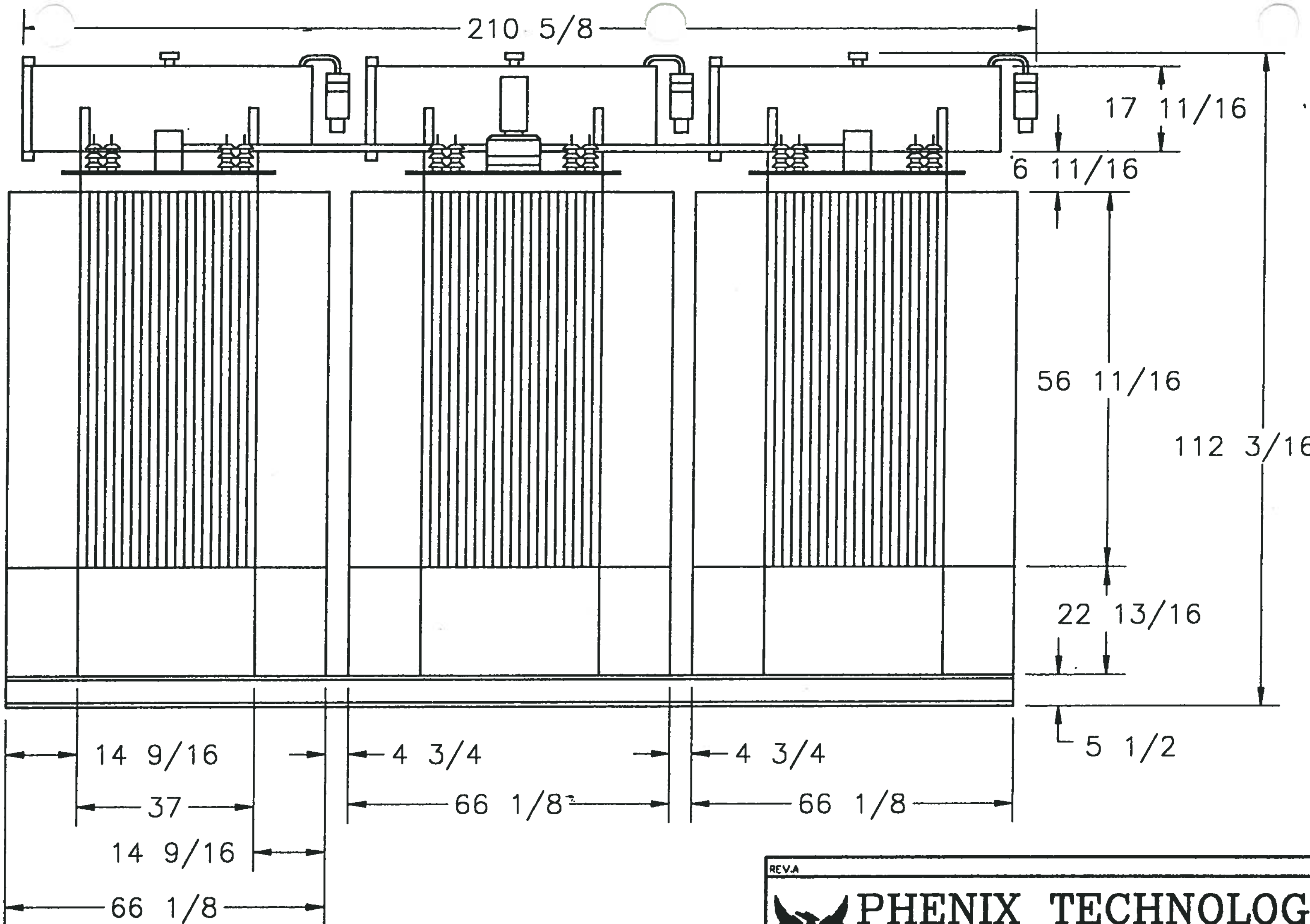


REV.A

PHENIX TECHNOLOGIES
INDUSTRIAL DRIVE, ACCIDENT MD. 21520

DATE	FILE	APVD BY:
TITLE: VARIABLE TRANSFORMER SYSTEM THOMA		REV BY
		DWN BY

SER NO	MODEL NO	DWG NO	DISK NO



VARIABLE TRANSFORMER
SYSTEM – THOMA
POWER – 3000kVA CONTINUOUS
PRIMARY – 4160V
SECONDARY – 0–4300V

CONNECTION – Dy
TOTAL WT. – 40920 lbs.
OIL WT. – 8360 lbs.
FREQUENCY – 60Hz

REV.A			
PHENIX TECHNOLOGIES INDUSTRIAL DRIVE, ACCIDENT MD. 21520			
DATE	FILE		APVD BY:
TITLE VARIABLE TRANSFORMER SYSTEM THOMA			REV BY DWN BY
SER NO	MODEL NO	DWG NO	DISK NO

DESIGN AND PERFORMANCE OF TOROIDAL VARIABLE TRANSFORMERS

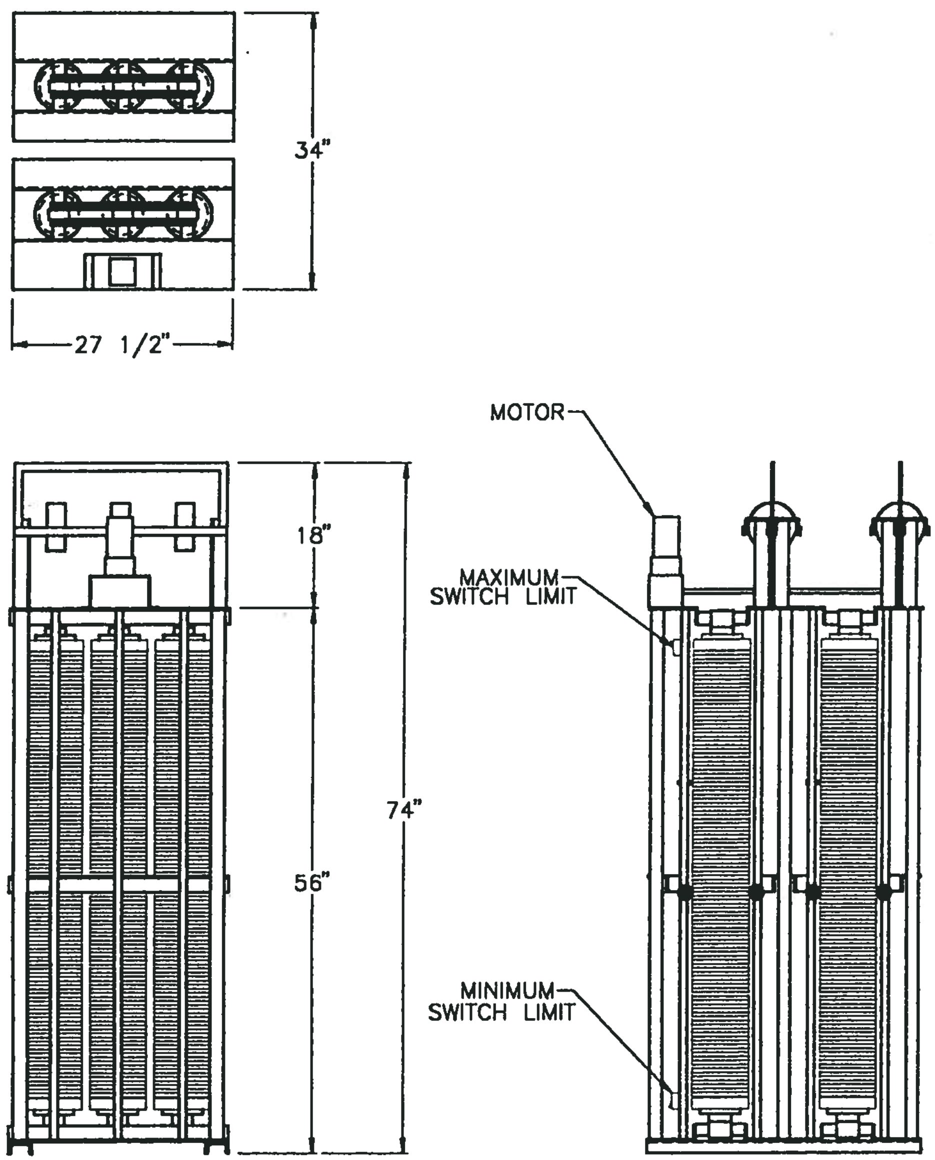
A TOROIDAL VARIABLE TRANSFORMER (trade name "VARIAC") has a single layer of non-insulated wire wound onto a toroidal core. The brush-holder assembly moves radially over the non-insulated wire, producing a quasi-stepless, sinusoidal waveform with negligible distortion.

- The short-circuit impedance varies with brush-holder position over a range of 10% to 1% as output varies from 0.1 to 1 (per unit).
- The voltage resolution is about 0.7 V/turn.
- Approx. 92 - 98% efficient.
- Primary application is for low to medium power control.
- Input voltage range 115 - 480 VAC.
- Output voltage not more than 1.15 times input voltage.
- Low reactance design produces negligible power factor reduction.
- Overload capability is limited.

DESIGN AND PERFORMANCE OF COLUMN-TYPE VARIABLE TRANSFORMERS

A COLUMN-TYPE VARIABLE TRANSFORMER (CTVT) consists of a single layer coil on which carbon rollers make electrical contact whith each successive turn of the winding. Single- or three-phase units are possible. The winding is helical which allows three-phase units to be built with a three-legged core as in a conventional transformer. The turns are insulated with glass tape and a vertical track is ground through the surface insulation to expose each turn of the winding. The carbon rollers run the full length of a silver or nickel coated copper track to provide the continuously variable tapping point. The rollers rotate as they travel along the coil face, so the wear is extremely low compared to sliding brushes.

- The short-circuit impedance varies with brush-holder position over a range of 10% to 1% as output varies from 0.1 to 1 (per unit).
- The voltage resolution is about 0.7 V/turn.
- Approx. 95 - 98% efficient.
- Primary application is for medium power control.
- Input voltage range 115 - 1000 VAC.
- Output voltage not more than 1.15 times input voltage.
- Overload capability is ten times rated current.



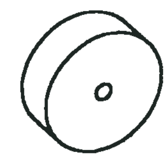
* HEIGHT AND WEIGHT MAY VARY WITH FINAL DESIGN

EST. WT.: 1700 lbs

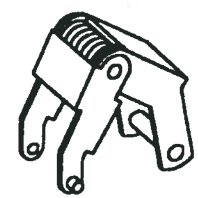
REV A			
PHENIX TECHNOLOGIES INDUSTRIAL DRIVE, ACCIDENT MD. 21520			
DATE	FILE		APVD BY:
TITLE COLUMN TYPE VARIABLE TRANSFORMER			REV BY DWN BY
SER NO	MODEL NO	DWG NO	DISK NO

BILL OF MATERIAL

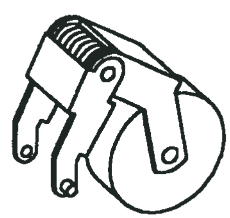
ITEM	QUAN	DESCRIPTION	PT NO
1		3 ROLLER HOLDER	1891916
2		ROLLER, 35mm	1891918
3		ROLLER, 40mm	1891919
4		SNAPPER	1891915
5		4 ROLLER HOLDER	1891917



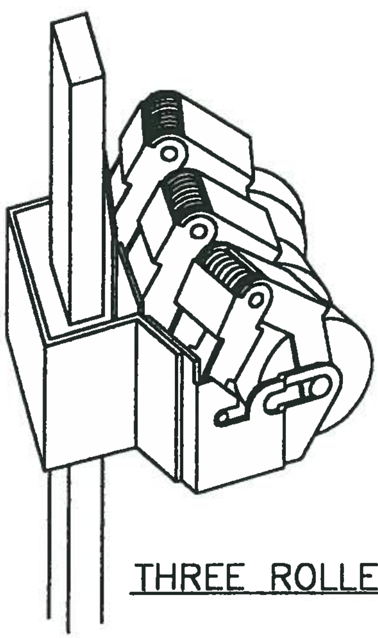
ROLLER



SNAPPER



SNAPPER WITH ROLLER



THREE ROLLER ASSY

REV.A

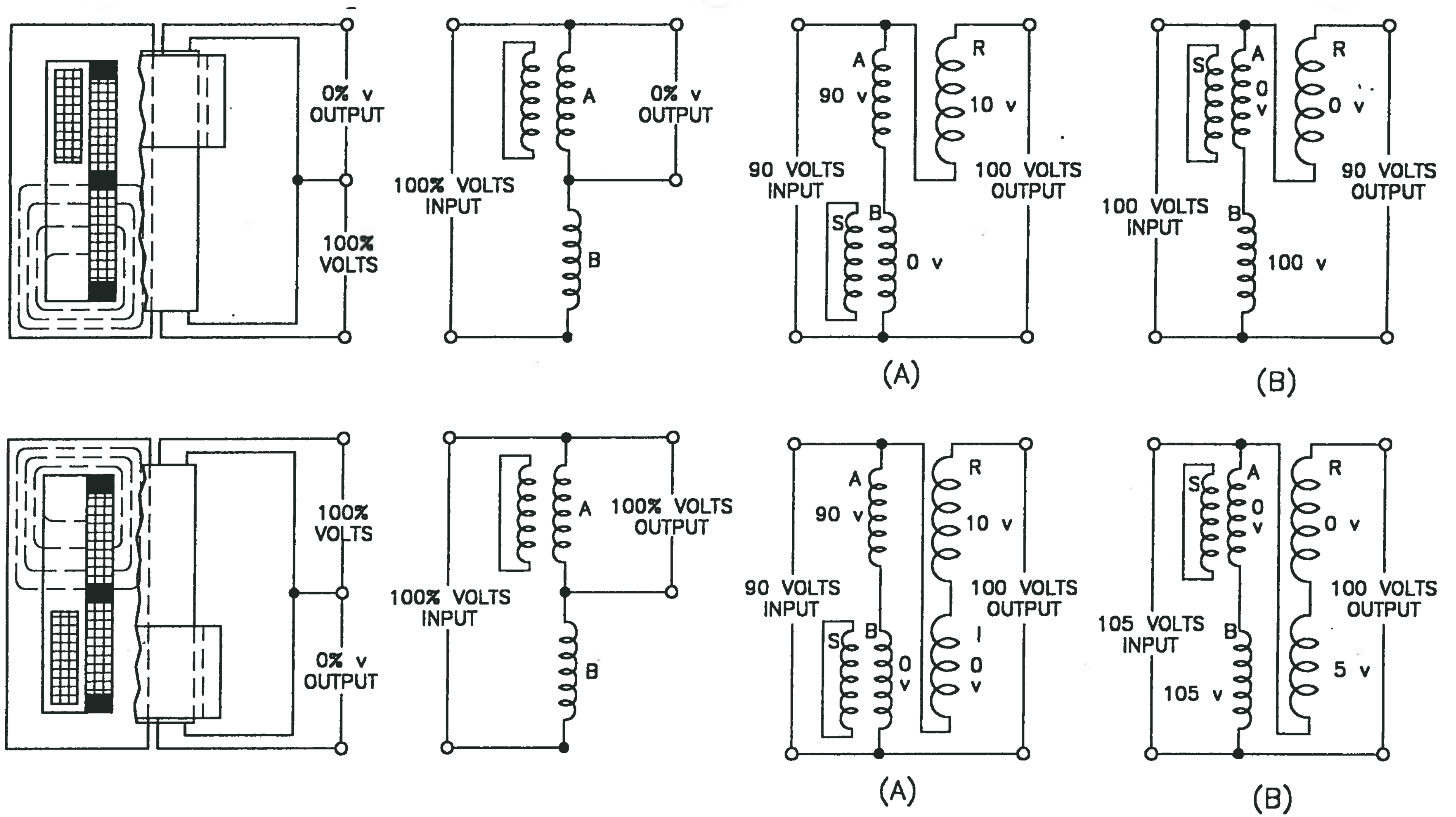
PHENIX TECHNOLOGIES
INDUSTRIAL DRIVE, ACCIDENT MD. 21520

DATE 4-27-95	FILE	APVD BY:
TITLE KVT REGULATOR BRUSH ASSY		REV BY
		DWN BY RCR
SER NO	MODEL NO	DWG NO / DISK NO

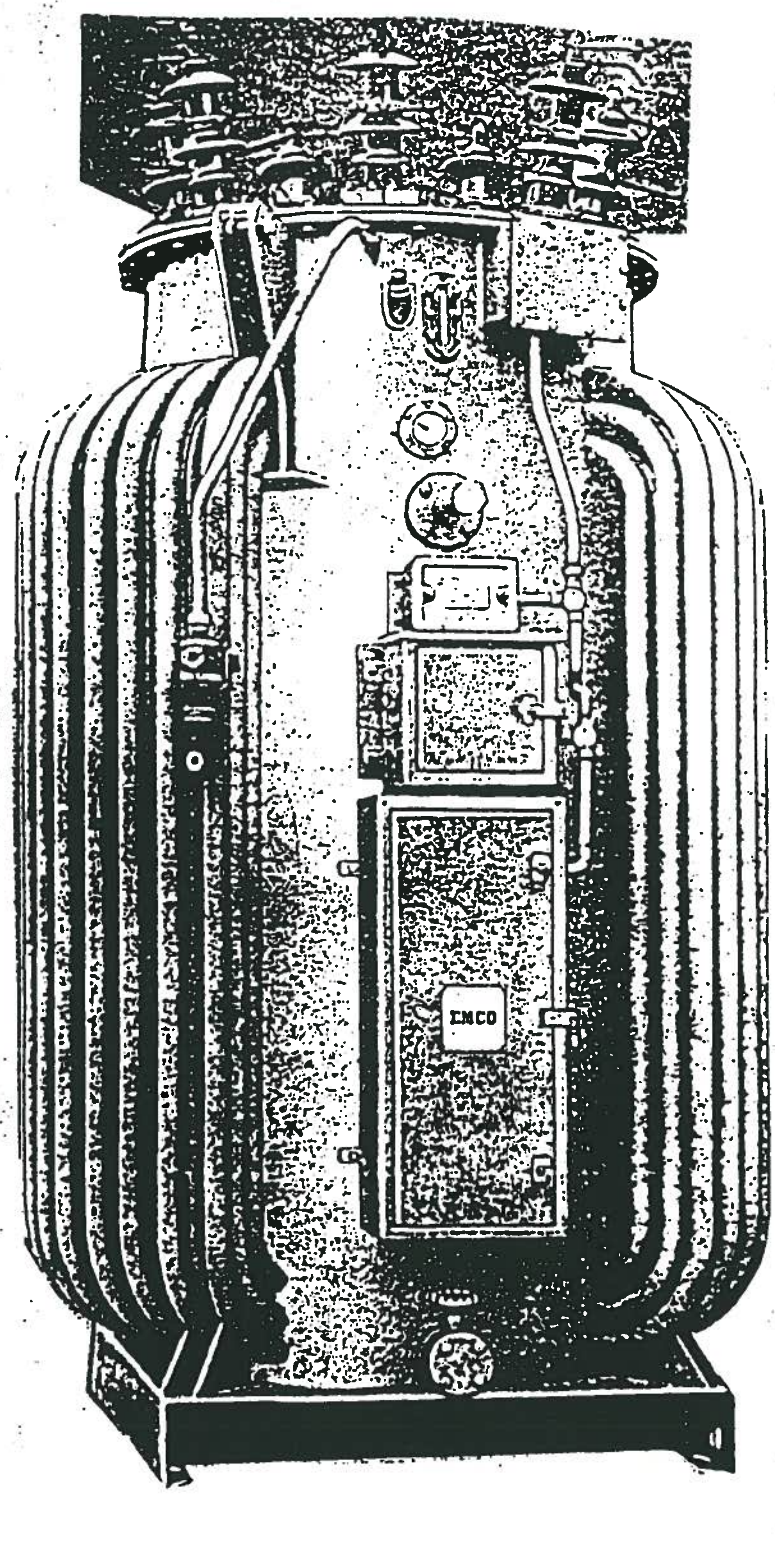
DESIGN AND PERFORMANCE OF MOVING-COIL VARIABLE TRANSFORMERS

A MOVING-COIL VARIABLE TRANSFORMER consists of two fixed coils wound on the upper and lower halves of a magnetic core and connected in series opposition. A third coil of the same length as the other two is short-circuited and free to move over the two fixed coils. Moving the coil varies the impedance of the fixed coils and changes the voltage across them. A MOVING-COIL VARIABLE TRANSFORMER is as maintenance-free as a system with moving parts can be.

- Short-circuit impedance is very low.
- The voltage is adjusted continuously without steps.
- Primary application is for high-voltage control at power ratings ranging from a few kVA to several MVA.



REV.A			
PHENIX TECHNOLOGIES INDUSTRIAL DRIVE, ACCIDENT MD. 21520			
DATE	FILE		APVD BY:
TITLE MOVING COIL VOLTAGE REGULATOR			REV BY
			DWN BY
SER NO	MODEL NO	DWG NO	DISK NO


EMCO

VARIABLE VOLTAGE-REGULATING TRANSFORMERS FOR RESEARCH AND TESTING

All of the VARIABLE VOLTAGE-REGULATING TRANSFORMERS previously mentioned can be used to control the input voltage of test transformers. These VARIABLE VOLTAGE-REGULATING TRANSFORMERS fullfill more or less the following requirements:

- Low induced line harmonics as defined by the *Ratio of Peak-Voltage to RMS Voltage = Square Root of 2.*

- A continuous or near continuous variable voltage adjustable from zero.

- A higher-impedance (VARIAC & CTVT) at low voltage for protection against a short-circuited test specimen.

- Lagging power factor (especially THOMA) for partially compensating leading power factor from capacitive loads such as during tests of high-voltage insulation, cables, or bushings.

AUTOTRANSFORMER PROPERTIES

- Autotransformer have only one winding. This winding is used as the primary and the secondary.

- The ideal transformer law $E1 / E2 = N1 / N2$ is valid.

- The primary voltage E1 is shifted approx. 180° compared to the secondary voltage E2.

- The current I1 is also shifted approx. 180° compared to current I2.

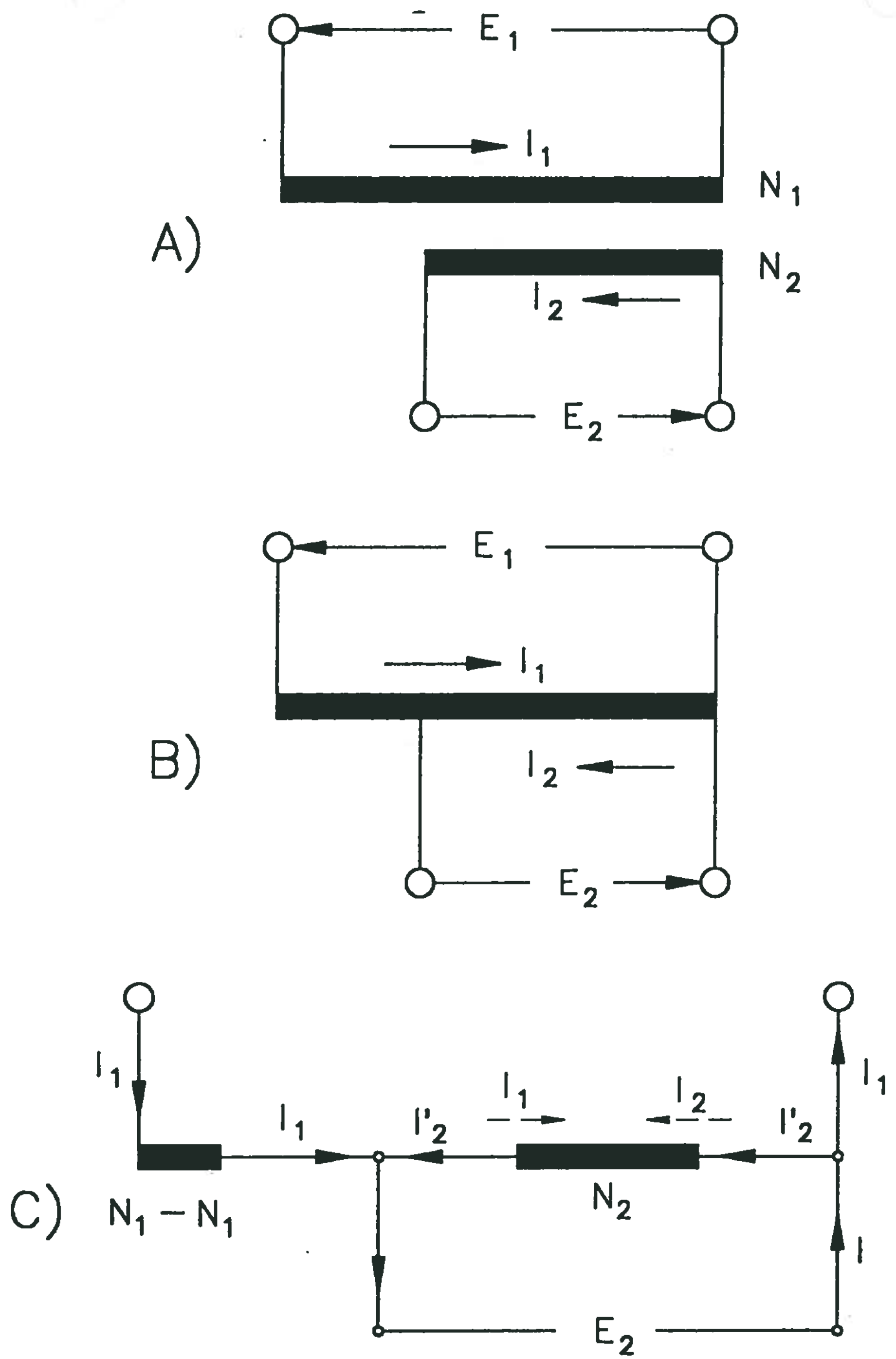
- The "common" winding carries a current $I'2 = I2 - I1$. The conductor area can be smaller compared to a conventional two-winding transformer. The current in the load is $I = I1 + I'2$.

- The weight and losses are reduced compared to a conventional two-winding transformer *with the same VA rating.*

- The disadvantages of autotransformers include:

  - No electrical isolation between Primary and Secondary.

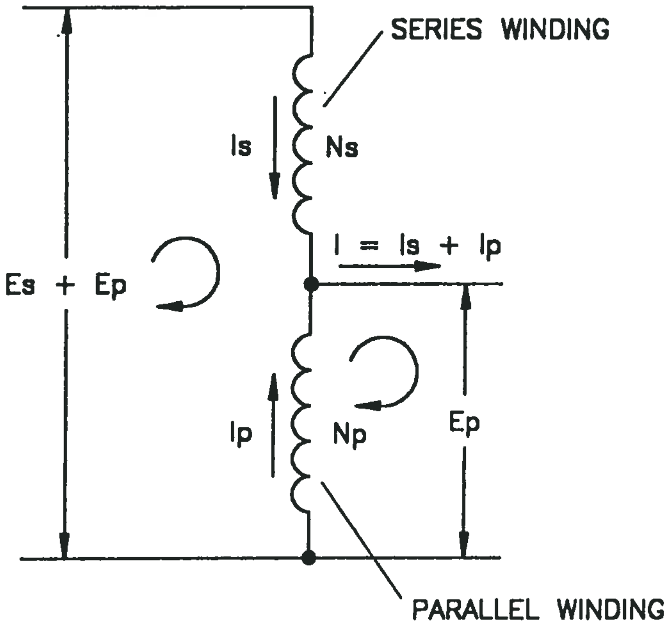
  - The short-circuit impedance depends on the turns ratio Ns / Np. Autotransformers are not short-circuit proof.

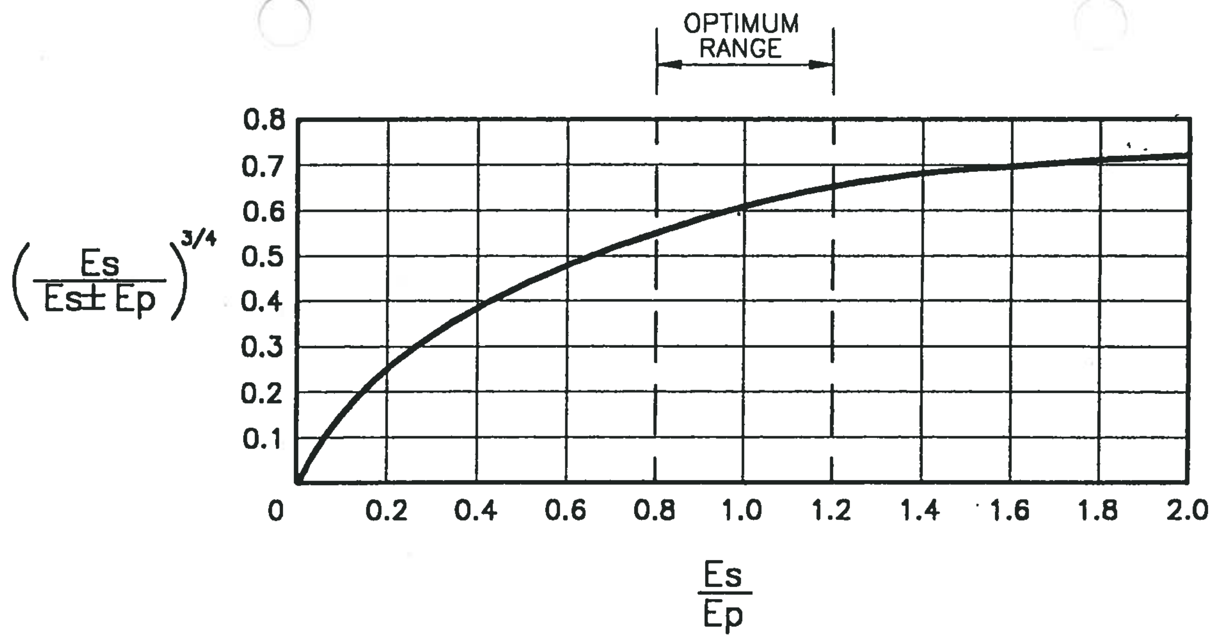


$$I = \frac{I'_2 \times N_1}{N_1 - N_2} = \frac{I_1 \times N_1}{N_2}$$

$$\frac{I}{I_1} = \frac{N_1}{N_2}$$

REV.A			
PHENIX TECHNOLOGIES INDUSTRIAL DRIVE, ACCIDENT MD. 21520			
DATE 4-26-95	FILE		APVD BY:
TITLE AUTO TRANSFORMER PRINCIPLE			REV BY
			DWN BY
SER NO	MODEL NO	DWG NO PAGE -1-	DISK NO





Es = VOLTAGE ACROSS THE SERIES WINDING
Ep = VOLTAGE ACROSS THE PARALLEL WINDING
Ns = SERIES WINDING
Np = PARALLEL WINDNING
Is = CURRENT IN THE SERIES WINDING
Ip = CURRENT IN THE PARALLEL WINDING
P = POWER OF A DOUBLE WINDING TRANSFORMER [kVA]
P = POWER THROUGHPUT OF A AUTO TRANSFORMER [kVA]
G = WEIGHT OF A DOUBLE WINDING TRANSFORMER
Gauto = WEIGHT OF A AUTO WINDING TRANSFORMER
V = TRANSFORMER LOSSES OF A DOUBLE WINDING TRANSFORMER
Vauto = TRANSFORMER LOSSES OF A AUTO WINDING TRANSFORMER
Edwsc = SHORT CIRCUIT VOLTAGE OF A DOUBLE WINDING TRANSFORMER
Eautosc = SHORT CIRCUIT VOLTAGE OF A AUTO WINDING TRANSFORMER

1) $\frac{Es}{Ep} = \frac{Ns}{Np}$

2) $Is \times Ns - Ip \times Np = 0$

3) $P = Es \times Is = Ep \times Ip$

4) $P\ throughput = (Es + Ep) \times Is = Ep \times (Ip + Is)$

5) $P\ throughput = P \times \left(\frac{Ep}{Es} \pm 1\right)$

6) $P = P\ throughput \times \left(\frac{Es}{Es \pm Ep}\right)$

7) WEIGHT $Gauto \approx G \left(\frac{Es}{Ep \pm Es}\right)^{3/4}$

8) TRANSFORMER LOSSES $Vauto \approx V \left(\frac{Es}{Ep \pm Es}\right)^{3/4}$

9) $Eautosc = \frac{Es}{Ep \pm Es}\ Edwsc$

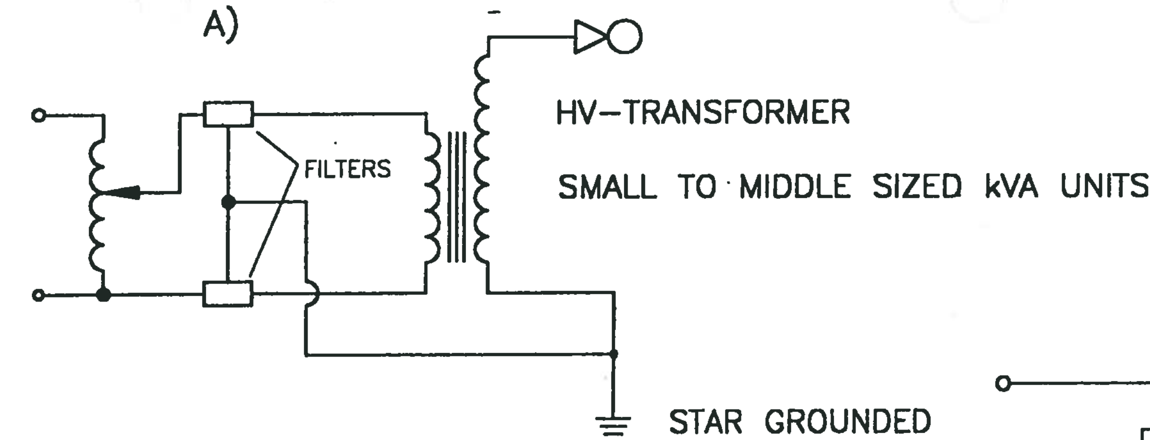
REV.A

PHENIX TECHNOLOGIES
INDUSTRIAL DRIVE, ACCIDENT MD. 21520

DATE 4-26-95	FILE	APVD BY:
TITLE AUTO TRANSFORMER PRINCIPLE		REV BY
		DWN BY

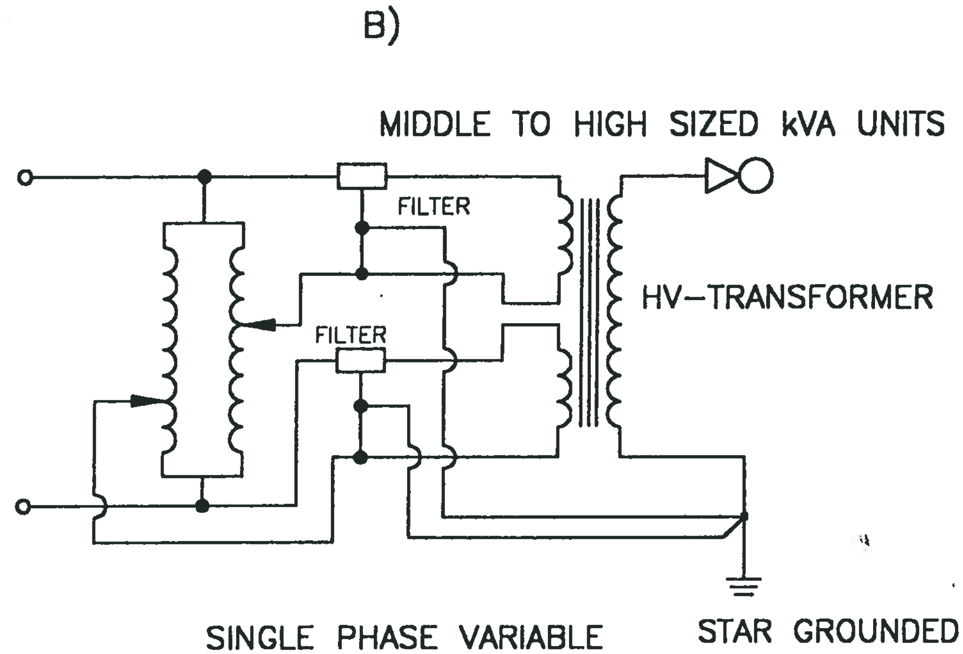
SER NO	MODEL NO	DWG NO PAGE -2-	DISK NO

A)



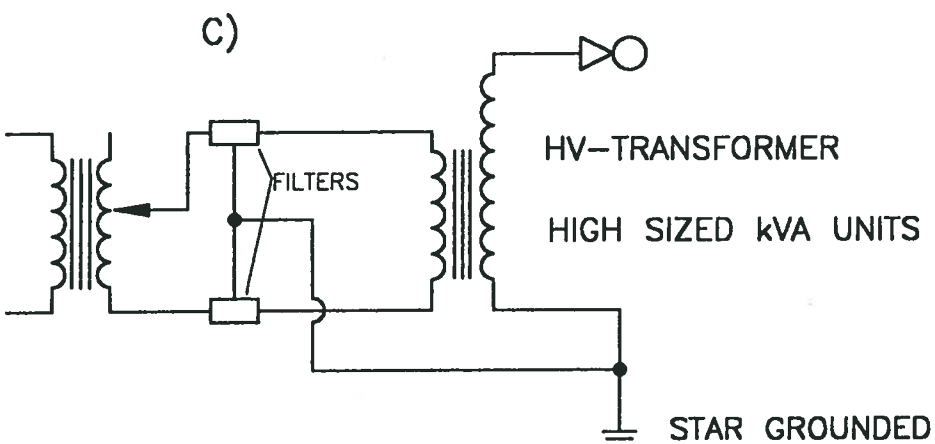
SINGLE PHASE VARIABLE
REGULATING TRANSFORMER
EX: TOROIDAL TRANSFORMER

B)



SINGLE PHASE VARIABLE
REGULATING TRANSFORMER
WITH ± DESIGN
EX: COLUMN TYPE REGULATOR

C)



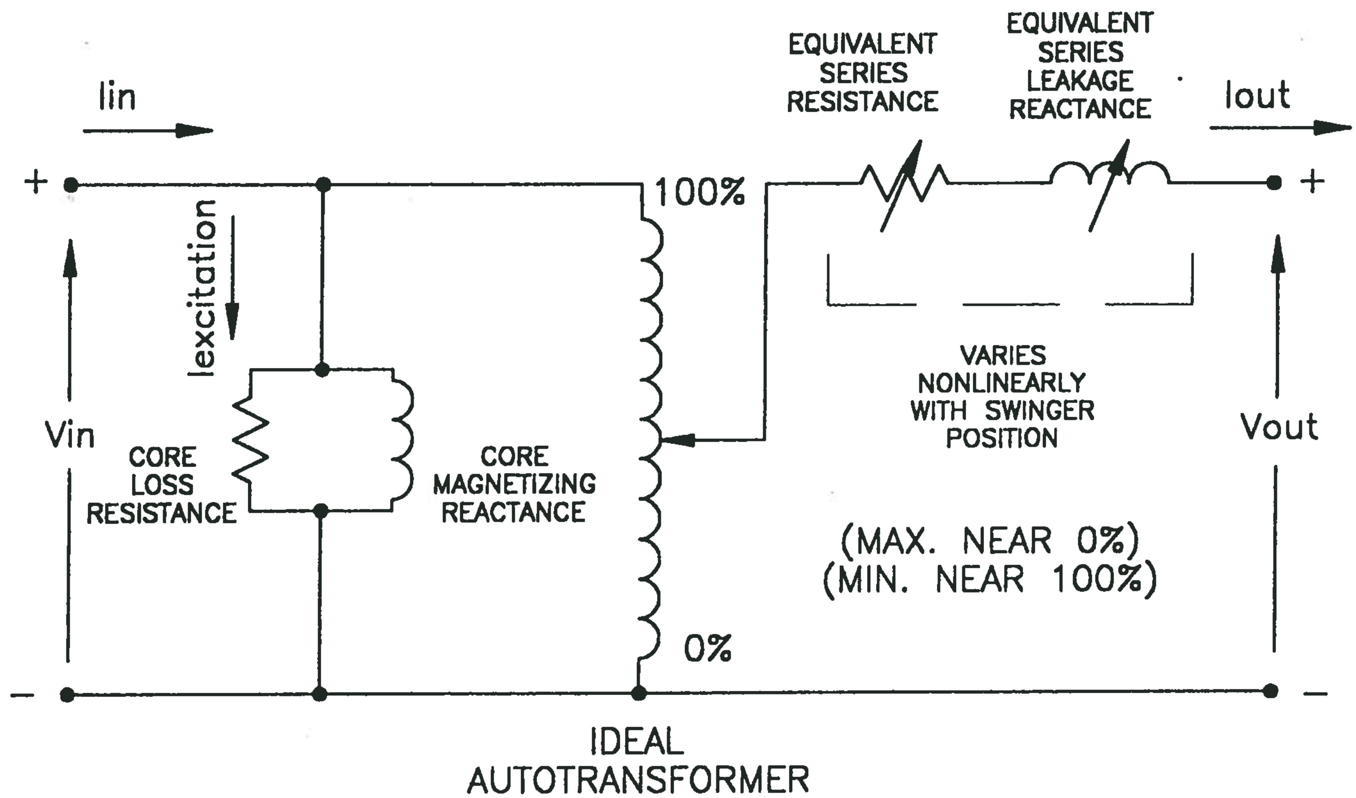
SINGLE PHASE VARIABLE
REGULATING TRANSFORMER
DOUBLE WINDING TRANSFORMER
EX: THOMA–VARIABLE TRANSFORMER

REV.A

PHENIX TECHNOLOGIES
INDUSTRIAL DRIVE, ACCIDENT MD. 21520

DATE 4–26–95	FILE	APVD BY:
TITLE COMMON ELECTRICAL CIRCUITS		REV BY
		DWN BY

SER NO	MODEL NO	DWG NO	DISK NO



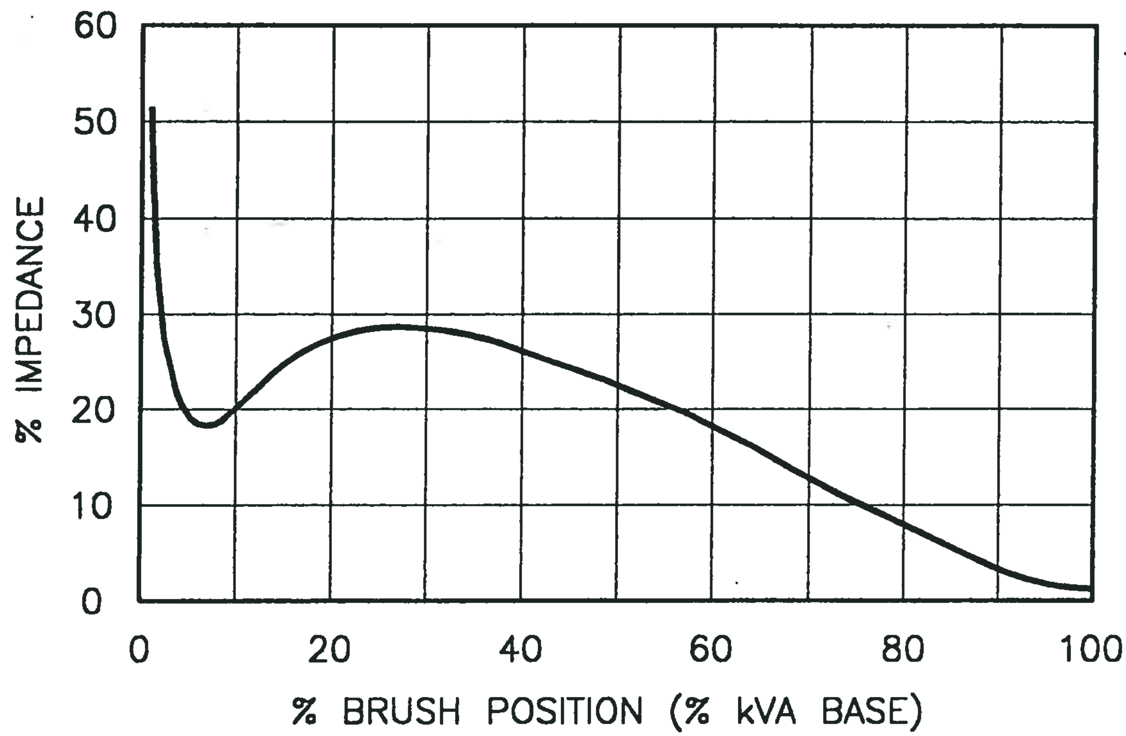
REV.A

PHENIX TECHNOLOGIES
INDUSTRIAL DRIVE, ACCIDENT MD. 21520

DATE 4-26-95	FILE	APVD BY:
TITLE EQUIVALENT CIRCUIT VARIABLE AUTO TRANSFORMER		REV BY
		DWN BY

SER NO	MODEL NO	DWG NO	DISK NO

AUTOTRANSFORMER IMPEDANCE CARACTERISTICS



BRUSH POSITION	INPUT V	OUTPUT I	% IMPEDANCE	% kVA BASE
2%	85V	34A	35%	2%
10%	47V	34A	20%	10%
25%	66V	34A	28%	25%
40%	64V	34A	27%	40%
50%	54V	34A	23%	50%
75%	22V	34A	9%	75%
90%	6.5V	34A	3%	90%
100%	0.79V	34A	0.3%	100%

REV.A

PHENIX TECHNOLOGIES
INDUSTRIAL DRIVE, ACCIDENT MD. 21520

DATE 4-27-95	FILE	APVD BY:
TITLE AUTOTRANSFORMER IMPEDANCE CHARACTERISTICS		REV BY
		DWN BY

SER NO	MODEL NO	DWG NO	DISK NO

OVERLOAD RATING OF VARIABLE VOLTAGE REGULATING TRANSFORMERS

- Overload limitations determined from Temperature - Time curves.

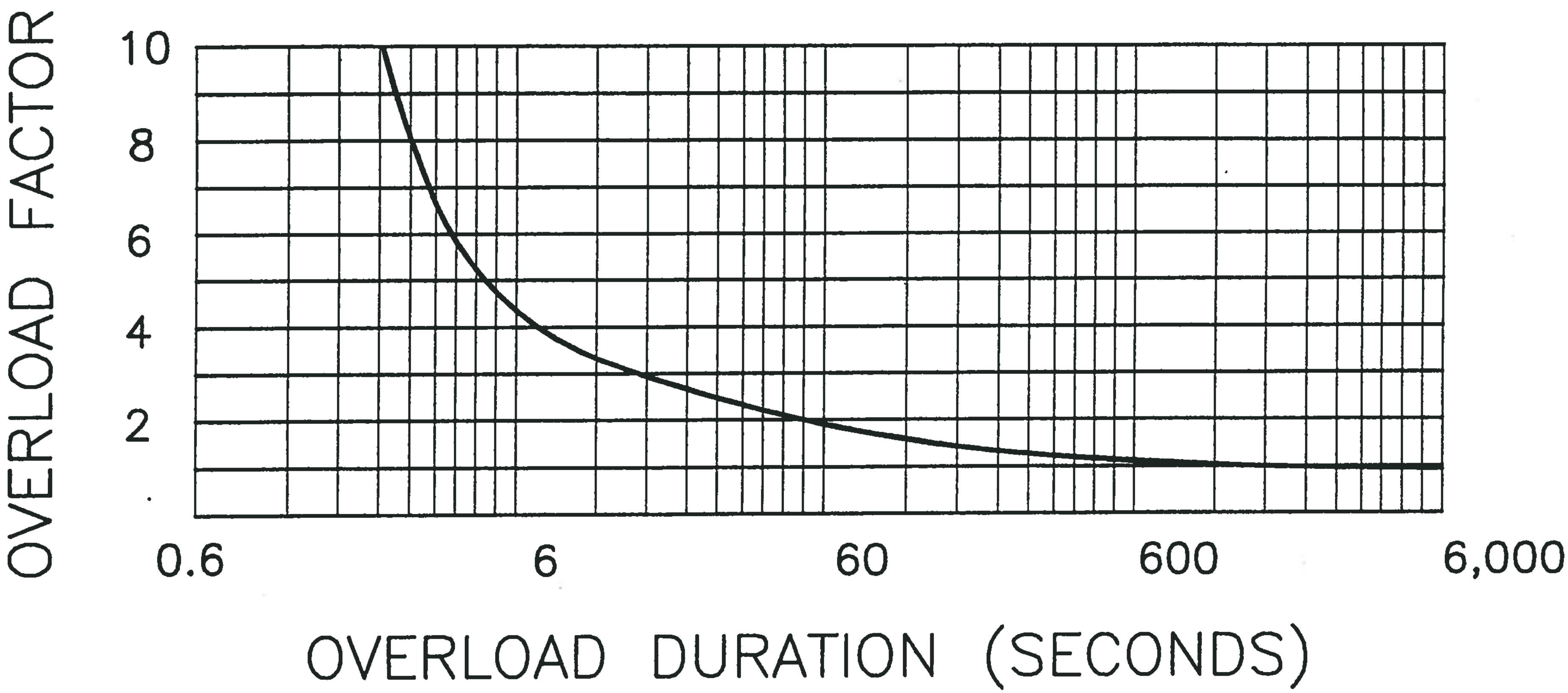
- Variable Voltage Regulating Transformers have several critical components EACH with DIFFERENT Temperature - Time curves (Thermal Characteristics).

- These components include: The winding, the current collector system, and the brush contact bar system.

- Typical Duty Cycle of high voltage test sets are:

  - 5 min. ON, 15 min. OFF, three times per hour.
  - 30 min. ON, 30 min. OFF.
  - 1 hour ON, 1 hour OFF.

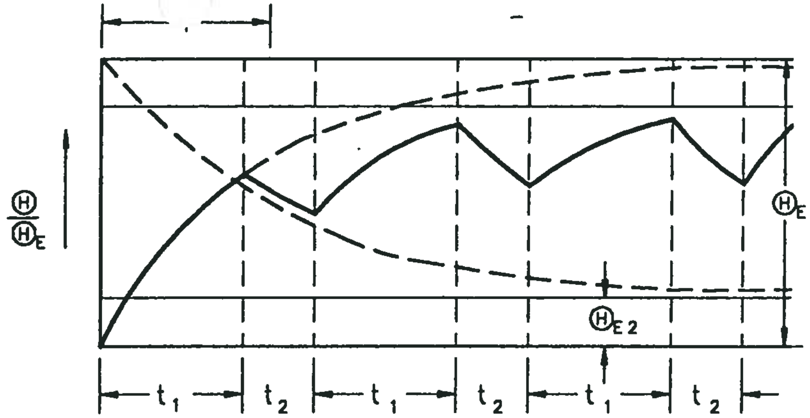
- Standard Overload Curves are available (e.g., CTVT OVERLOAD).

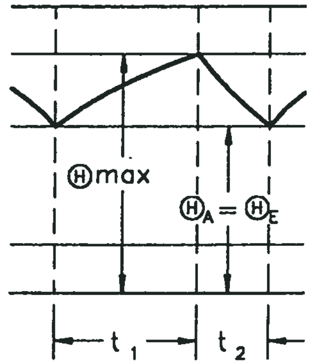


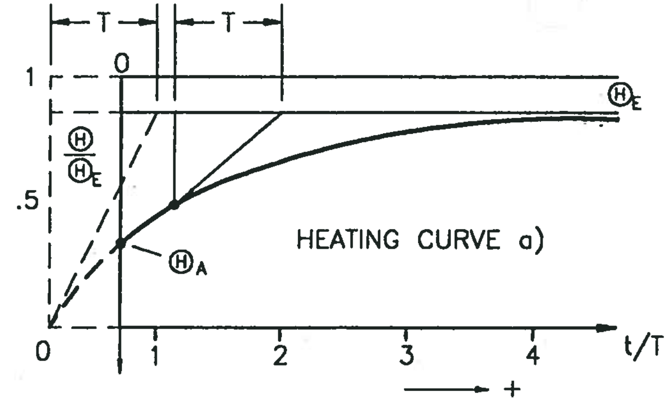
REV.A

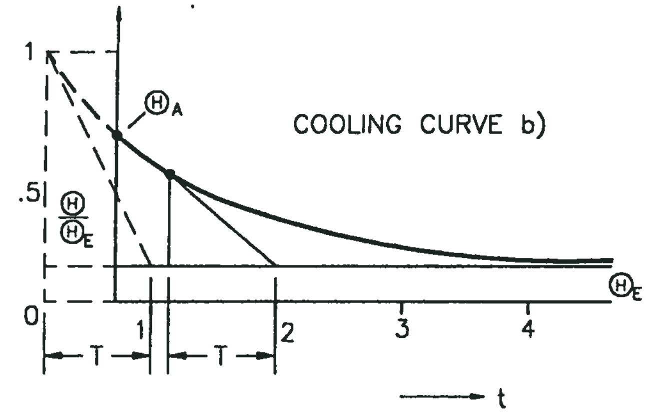
PHENIX TECHNOLOGIES
INDUSTRIAL DRIVE, ACCIDENT MD. 21520

DATE	FILE		APVD BY:
TITLE: CTVT OVERLOAD			REV BY
			DWN BY
SER NO	MODEL NO	DWG NO	DISK NO









t/T	e−t/T	t/T	e−t/T	t/T	e−t/T
0.00	1.000	0.60	0.549	1.40	0.247
0.05	0.951	0.65	0.522	1.50	0.223
0.10	0.905	0.70	0.497	1.60	0.202
0.15	0.860	0.75	0.472	1.70	0.183
0.20	0.819	0.80	0.449	1.80	0.165
0.25	0.779	0.85	0.429	1.90	0.150
0.30	0.741	0.90	0.407	2.00	0.135
0.35	0.705	0.95	0.387	2.20	0.111
0.40	0.670	1.00	0.368	2.40	0.091
0.45	0.638	1.10	0.333	2.60	0.074
0.50	0.607	1.20	0.301	2.80	0.061
0.55	0.577	1.30	0.273	3.00	0.050
				4.00	0.018

CURVE a

$\Theta_A = 0$

$t = T \longrightarrow \Theta = (1-.368)\ \Theta_E \approx 63$ OF Θ_E

$t = 4 \times T \longrightarrow \Theta \approx 1.8\%$ BELOW Θ_E

Θ = OVER TEMPERATURE

Θ_E = FINAL OVER TEMPERATURE

Θ_A = STARTING OVER TEMPERATURE

t = TIME

T = THERMAL TIME CONSTANT

t_1 = TIME INTERVAL HEATING UP

t_2 = TIME INTERVAL COOLING DOWN

Θ_{E1} = FINAL OVER TEMPERATURE AFTER HEATING UP

Θ_{E2} = FINAL OVER TEMPERATURE AFTER COOLING DOWN

REV.A

PHENIX TECHNOLOGIES

INDUSTRIAL DRIVE, ACCIDENT MD. 21520

DATE 4-27-95	FILE	APVD BY:
TITLE OVER TEMPERATURE CURVE CLASSIC THEORY		REV BY
		DWN BY
SER NO	MODEL NO	DWG NO	DISK NO

OVERLOAD RATINGS

- Consider the following two examples published by Brentford, UK for their COLUMN TYPE VARIABLE TRANSFORMER.

I. Single-Event Overloads (from Ambient Temp.)

$$R^2 t_1 = 45 \text{ for coils over 55 A}$$

R = Ratio of overload to rated load current

t_1 = "ON" time in secs.

Example:

Assume the permissible overload current on a 75 A coil for 10 sec. has to be determined:

$$R = \sqrt{45/10} = 2.1 \text{ times or 157 A}$$

May be repeated every 15 min. over a four hour period.

OVERLOAD RATINGS (CONT.)

II. Repetitive Overloads

$$t_2 = 4\,(R^2\,t_1) - t_1$$

t_2 = "OFF" time in secs.

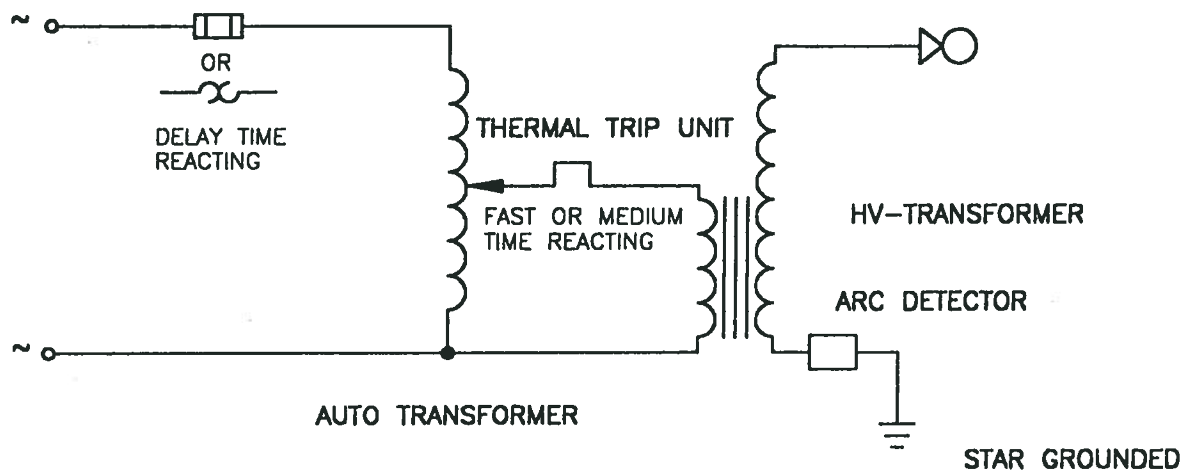
Example:

Assume that in a given case three times rated current is required on a 75 A winding (3 × 75 A = 225 A).

$$R^2 = 3^2 = 9$$

$$t_1 = 45/9 = 5\text{ s}$$

$$t_2 \geq (4 \times 45) - 5 = 175\text{ s}$$

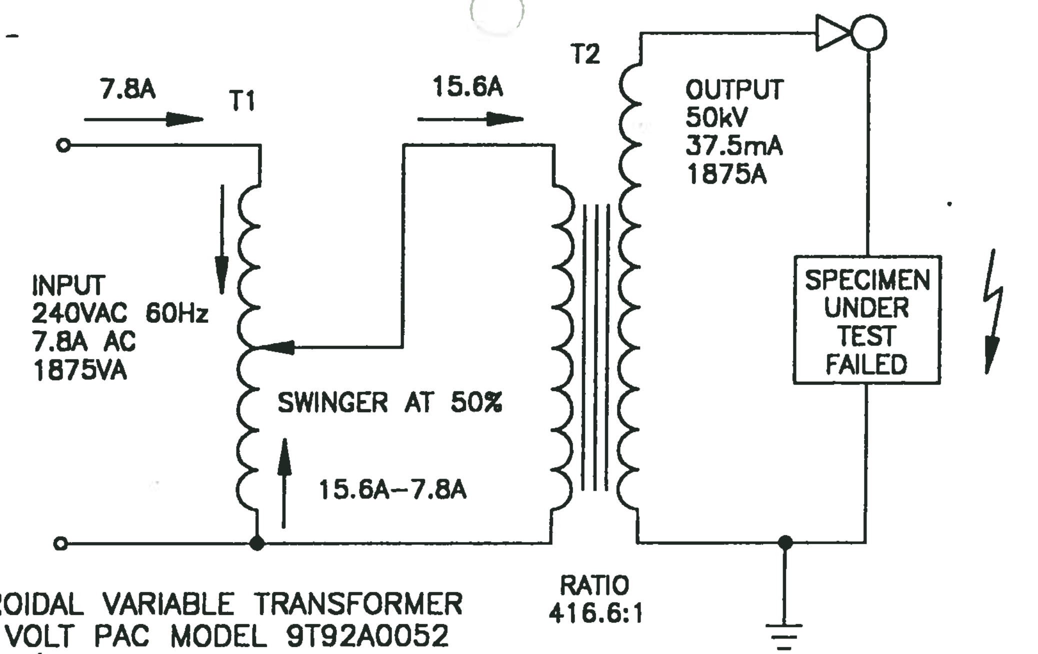


REV.A

PHENIX TECHNOLOGIES

INDUSTRIAL DRIVE, ACCIDENT MD. 21520

DATE 4-26-95	FILE	APVD BY:
TITLE OVERLOAD PROTECTION		REV BY
		DWN BY
SER NO	MODEL NO	DWG NO / DISK NO



T1 = TOROIDAL VARIABLE TRANSFORMER
GE VOLT PAC MODEL 9T92A0052
240V/0–240V
34A AC
0–8160VA

T2 = HV TRANSFORMER
240V/31.25A
100kV/75mA
Zsc = 18%

Zsc = AMOUNT VALUE OF SHORT CIRCUIT IMPEDANCE IN [Ω]
Iscp = AMOUNT VALUE OF PRIMARY SHORT CIRCUIT CURRENT [A]
Iscs = AMOUNT VALUE OF SECONDARY SHORT CIRCUIT CURRENT [mA]
Zsc_{T1} = AMOUNT VALUE OF SHORT CIRCUIT IMPEDANCE OF T1 [Ω]

SHORT CIRCUIT CURRENT AT 50% INPUT VOLTAGE OF HV TRANSFORMER
SWINGER AT 50%
SEE DRAWING AUTO TRANSFORMER IMPEDANCE CARACTERISTICS (50%)
Zsc = 23%

$Zsc_{T1} = \frac{54V}{34A} = 1.59\,\Omega \quad Isc = \frac{240V}{1.59\Omega + 1.38\Omega} = 81A$

$Iscs = \frac{81A}{416.6} = 194mA$

REV.A				
PHENIX TECHNOLOGIES INDUSTRIAL DRIVE, ACCIDENT MD. 21520				
DATE 4–28–95	FILE		APVD BY:	
TITLE SHORT CIRCUIT CHARACTERISTICS (50%)			REV BY	
			DWN BY	
SER NO	MODEL NO	DWG NO	DISK NO	

SUMMARY

- The VARIABLE VOLTAGE-REGULATING TRANSFORMER has preferred performance characteristics for voltage regulation in applications requiring high power factor and low line harmonics.

- The engineer specifying equipment controlled by VARIABLE VOLTAGE-REGULATING TRANSFORMERS for research, testing, or manufacturing should consider:

  - The required kVA rating.

  - The required overload protection devices.

  - The requirements of the specific application (i.e., life-time, overload duty factor, working environment, etc.).