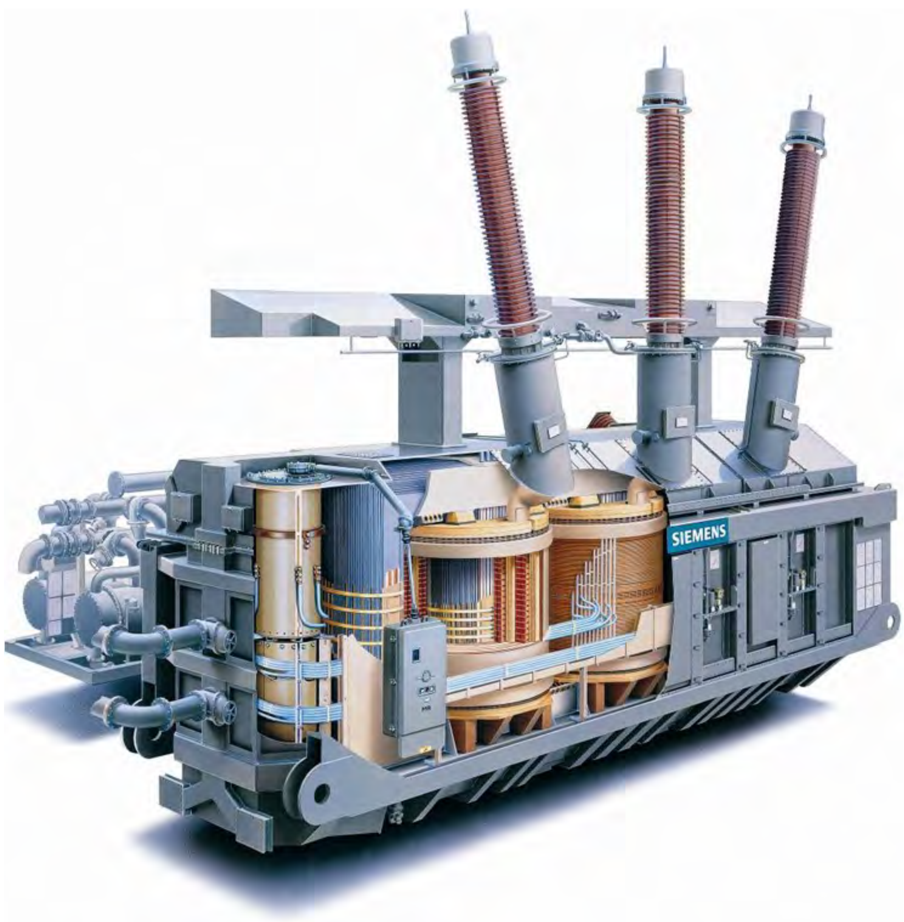
"Auto-transformers and Three-phase Transformers"



Experiment Objectives

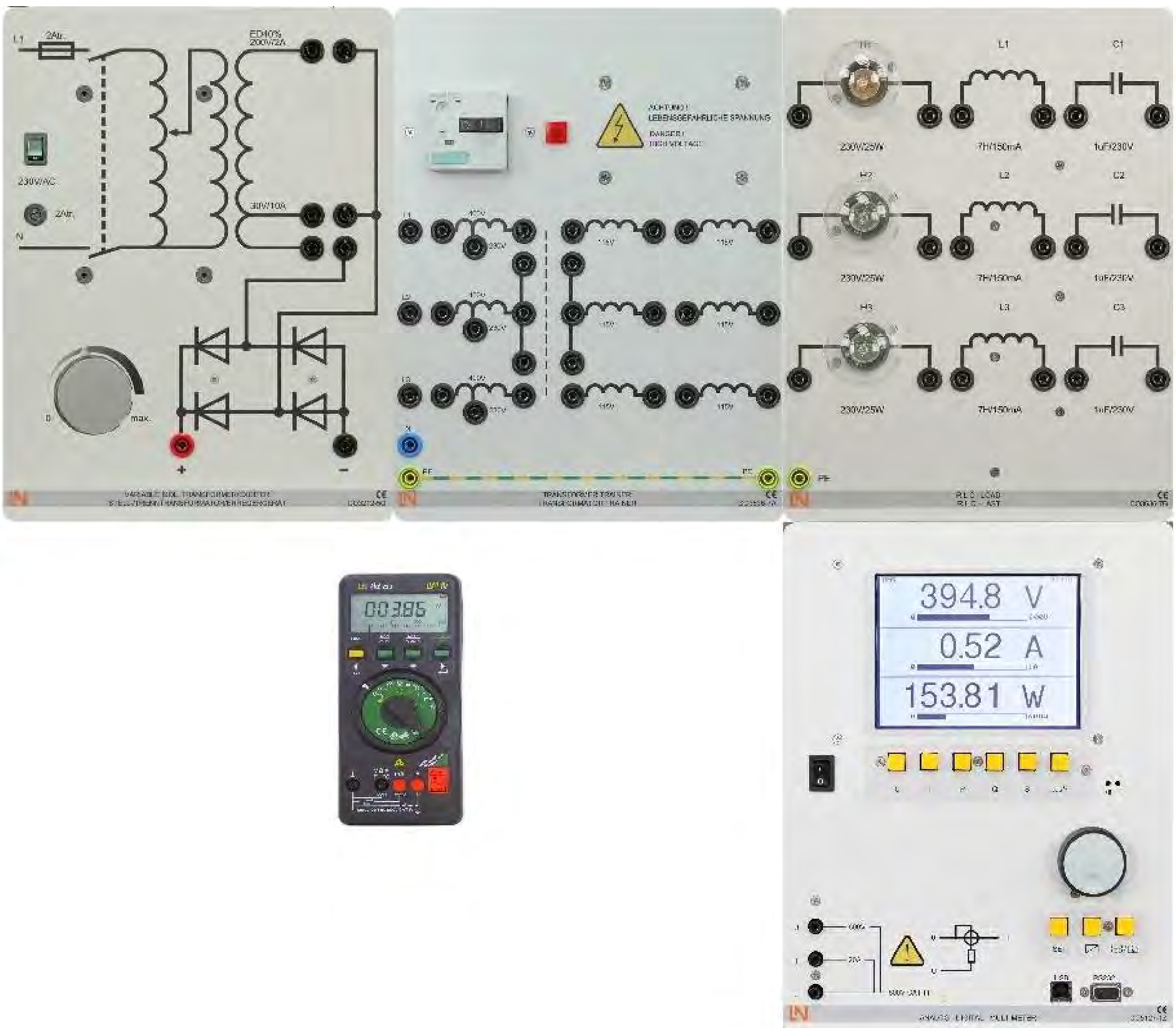
In the early days of the electricity industry, energy production and consumption were separated by short distances. Bridging of long distances with the direct current system of that time was not possible due to the high losses occurring on the lines. Economical transmission here is only possible by means of high voltages and correspondingly low currents. Conversion of electrical energy into any required voltage values can be easily realized with the help of transformers in the case of alternating current.

Transformers produced today range from small, single-phase models rated at a few watts to three-phase transformers with a power of around 1500 MVA. Small transformers are used in large numbers for electronic devices. Distribution or mains transformers with a power rating of 100 kVA to 2000 kVA serve to supply end consumers with 230 V / 400 V from medium-voltage grids. Machine transformers with powers of up to 1500 MVA are connected in series to turbo generators at power plants, and directly feed 230kV or 400kV grids.

- Purposes of transformers
- Design and operating principle of transformers
- Different types of transformers
- Auto-transformers's operation
- Step-up and step-down transformation
- Three-phase transformer in different circuits

Equipment

CO3636-7A	Transformer trainer	1
CO3636-7B	RLC load	1
CO3212-5Q	Variable/isolating transformer and excitation unit	1
CO5127-1Z	Analog/digital multimeter, wattmeter/power-factor meter	1
LM2319 or LM2321	Optional MetraHit Multimeter	1



CO3636-7A

The transformer trainer can be used to assemble and examine all circuits involving single-phase and three-phase transformers. The board incorporates a special transformer. Safeguarding is provided by a motor protection switch.

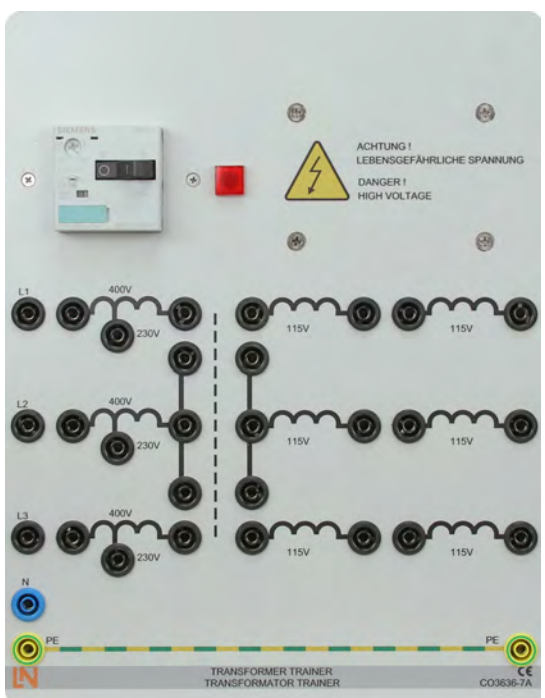
The following experiments can be carried out:

- Operation as a single-phase transformer.
- Determination of open-circuit voltages, transformation ratios and losses.
- Operation as an auto-transformer.
- Step-up and step-down transformation.
- Operation as a three-phase transformer in different circuits.

Technical data:

CO3636-7A7	
Power	100 VA
Primary side voltage	3 x 120 V/208 V, 60 Hz
Secondary side voltage	3 x 2 x 115 V
Secondary side current	145mA
Number of primary turns	0 - 120 V, 680 turns 120 V - 208 V, 493 turns
Number of secondary turns	2 x 0 - 115 V, 682 turns
Core	El 100 x 100 (3 UI60), M530 - 50A
Iron path length I_{Fe}	14.96 in (or 6.30 in for single-phase operation)
Iron cross-section A_{Fe}	0.9 in^2, taking into account the filling factor

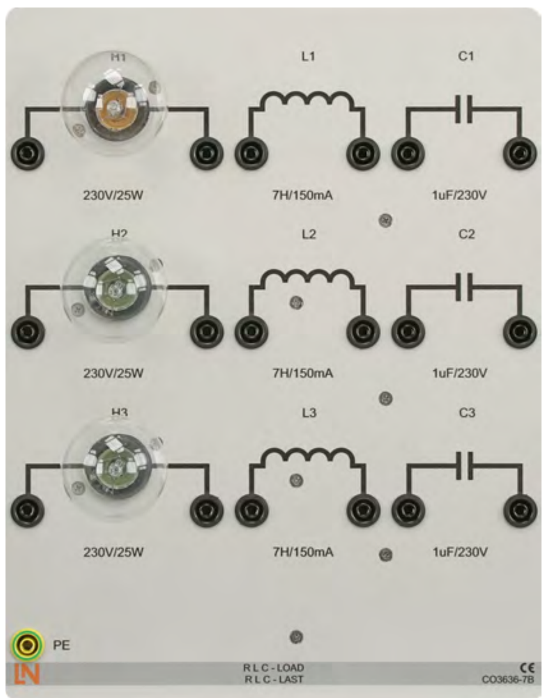
- Supply via mains cable.
- Safeguarding via motor protection switch.
- Height: 11.7 in.



CO3636-7B

The RLC load is suitable as a universal load for all transformer experiments.

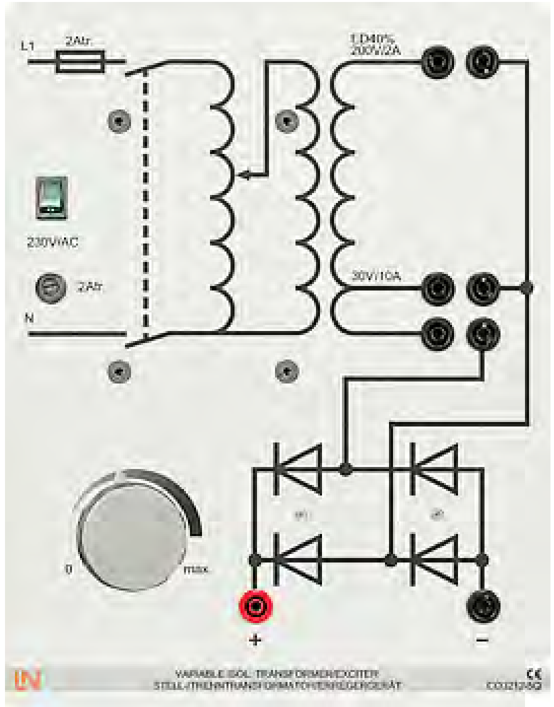
- Ohmic load: 3 incandescent lamps 230 V/25 W.
- Inductive load: 3 x 6,7 H/230 V.
- Capacitive load: 3 x 1 µF, 230 V~.
- Dimensions: 11.7 x 9 x 4.7 in (H x W x D).
- Weight: 2.3 kg.



CO3212-5Q

The variable/isolating transformer and excitation unit is for excitation of fields for DC, synchronous and multi-function electrical machines.

- Output voltage:
  - 0 ... 230 V, 2 A AC/DC
  - 0 ... 30 V, 10 A AC/DC
- Dimensions: 11.7 x 9 x 4.9 in (H x W x D).
- Weight: 12 kg



CO5127-1Z*

CO5127-1Z (*CO5127-1Z8 → 60 Hz) "Analog/digital multimeter" experiment panel:

Technical data:

- Measurement variables:
  - Voltage Current
  - Active power
  - Apparent power
  - Reactive power
  - Cosine φ
- Protection class II
- Interfaces:
  - USB

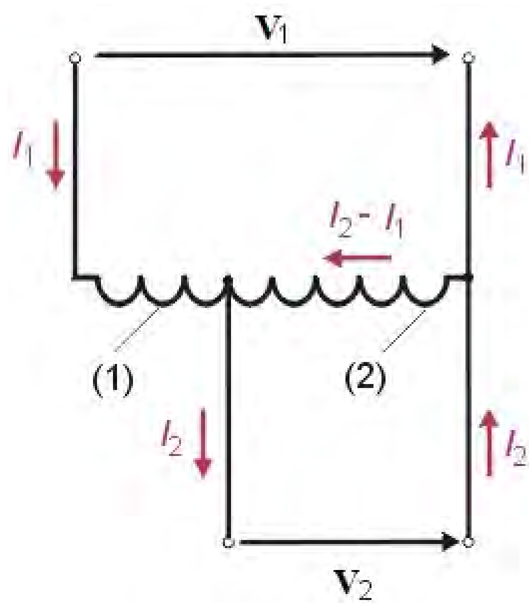
The manufacturer's instruction sheet can be found at manufacturer's instruction sheet.

Experiments

Auto-transformers

Design

The auto-transformer is a special type of transformer possessing a *common* winding for the primary and secondary sides. This type of transformer therefore does not incorporate two windings which are electrically separated from each other. The winding is divided into parallel and series sections. The auto-transformer's schematic design is illustrated next. The series winding (1) is for the upper voltage, the parallel winding (2) for the lower voltage.



The circuit resembles that of a voltage divider comprising resistors. However, this similarity is deceptive because the functionality is totally different: Whereas the voltage divider comprising resistors is simply able to split, i.e. reduce applied voltages, the auto-transformer is also able to raise voltages.

To step down voltages, a voltage V_1 is supplied to the series winding, and a (lower) voltage V_2 is tapped from the parallel winding as illustrated above. To step up voltages, a voltage V_1 is supplied to the parallel winding and a (higher) output voltage V_2 is tapped from the series winding. The voltage transformation ratio depends on the ratio between the numbers of turns, as in the case of a dual-winding transformer.

Example: An auto-transformer has a total of 300 turns, with the tap positioned at the 270th turn. A voltage of 198 V is supplied to the transformer. The output voltage at the series winding accordingly is:

$$\mathbf{V}_2 = \mathbf{V}_1 \cdot \frac{N_2}{N_1} = 198\text{V} \cdot \frac{300}{270} = 220\text{V}$$

Efficiency and Rated Performance

Under load, only the difference between the primary and secondary currents flows in the common section of the winding for the primary and secondary circuits; this section can therefore be manufactured using significantly reduced conductor cross-sections. A use of auto-transformers not only saves material, but also reduces current heat losses. The current flowing through the common winding section decreases as the transformation ratio approaches 1:1. Use of an auto-transformer is therefore particularly advantageous when the voltage transformation ratio does not deviate significantly from 1:1. Efficiencies of up to 99.8% can be achieved in such cases.

An auto-transformer's possible output power is known as its *throughput power* S_D. It is transferred partly via a conduction of current from the input winding to the output winding, and partly via induction. The greater the power transferred by conduction, the smaller the power to be transmitted via induction, given a fixed throughput power. This variable S_B determines the transformer's rated performance. Assuming that V_1 is the upper voltage and V_2 the lower voltage, the rated performance is governed by the following relationship:

$$\boxed{S_B = S_D \cdot \frac{\mathbf{V}_1 - \mathbf{V}_2}{\mathbf{V}_1}}$$

Because auto-transformers are not galvanically isolated from the grid due to their common winding, they should not be used as safety isolating transformers.

Case 1: Step-down Transformation

A: No Load

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 1.
2. Turn on the transformer trainer.

3. Record the voltages under no load in Table 1.
4. Turn off the transformer trainer.

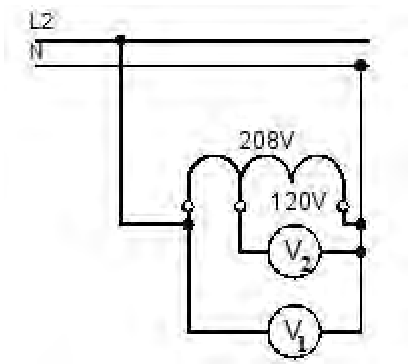


Figure 1:
Step-down No Load

B: Load

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 2.
2. Turn on the transformer trainer.
3. Record the voltages under load in Table 1.
4. Turn off the transformer trainer.

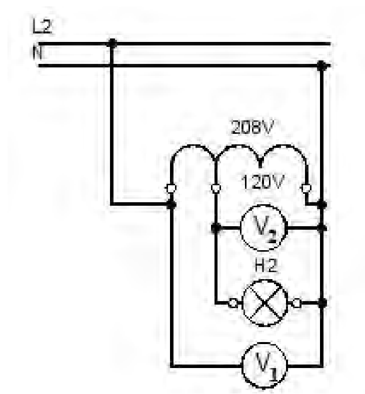


Figure 2:
Step-down with Load

Step-dowm Transformation			
No Load		Under Load	
V_1	V_2	V_1	V_2

Table 1

Case 2: Step-up Transformation

A: No Load

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 3.
2. Turn on the transformer trainer.
3. Record the voltages under no load in Table 2.
4. Turn off the transformer trainer.

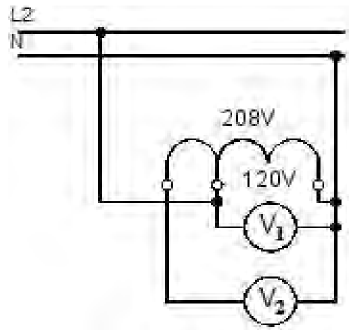


Figure 3:
Step-up No Load

B: Load

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 4.
2. Turn on the transformer trainer.
3. Record the voltages under load in Table 2.
4. Turn off the transformer trainer.

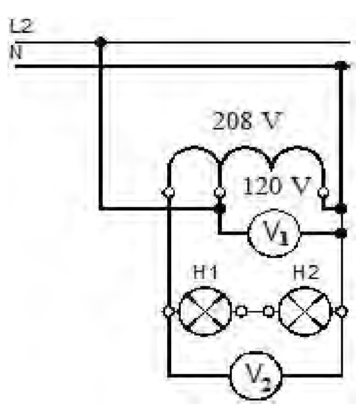
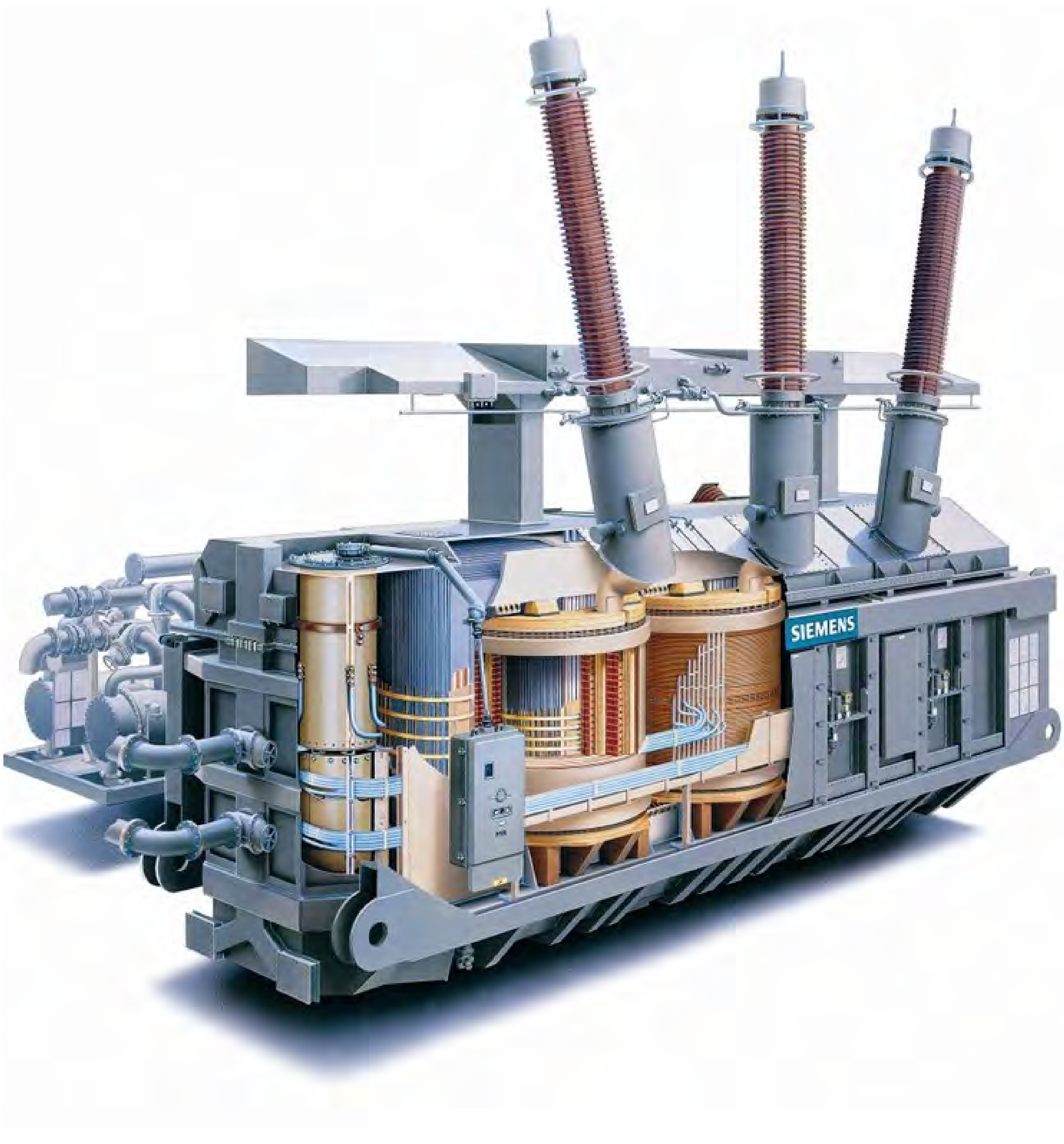


Figure 4:
Step-up With Load

Step-up Transformation			
No Load		Under Load	
V_1	V_2	V_1	V_2

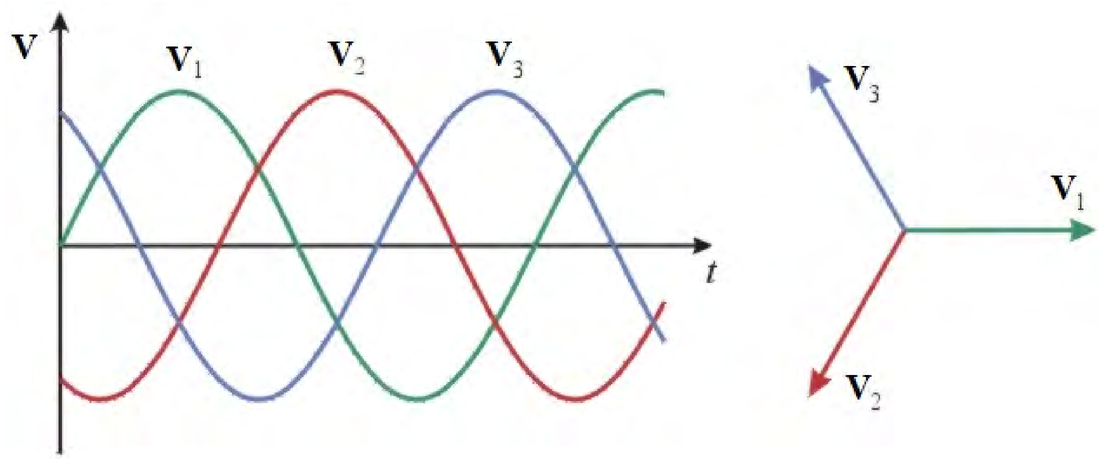
Table 2

Three-phase Transformers



Three-phase Transformer Design

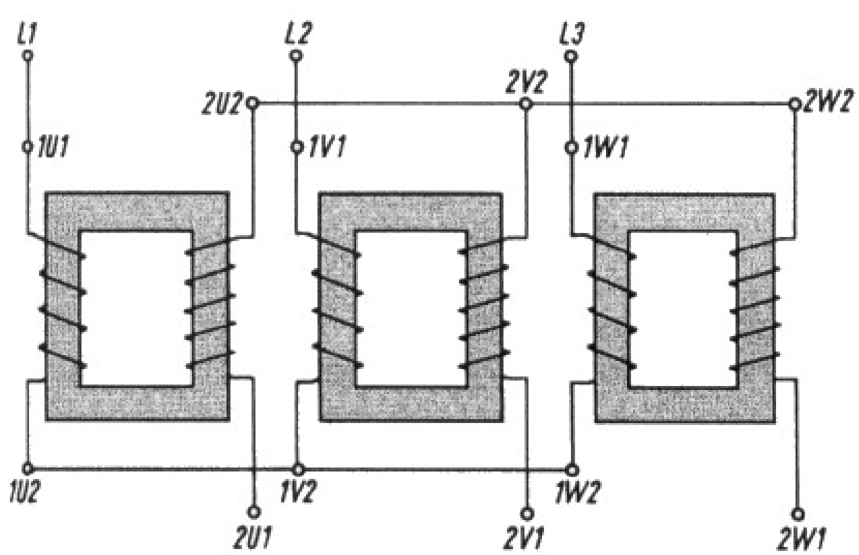
For reasons of economy, electrical energy is transmitted via three-phase systems instead of single-phase systems. The *three-phase systems* used for this purpose contain three equal variables, each comprising a single-phase alternating voltage displaced by 120° with respect to the others. Provided next is a depiction of the phase voltages' time characteristics, as well as the related vector diagram.



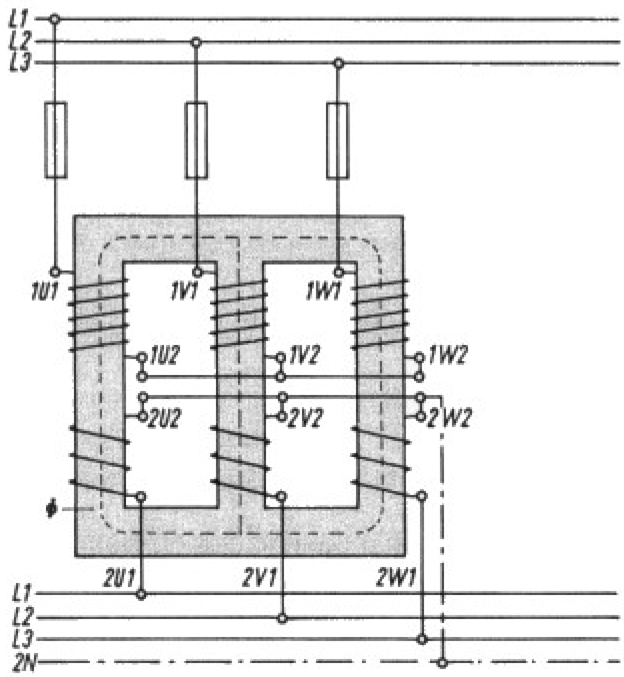
The phases here are usually named L1, L2 and L3.

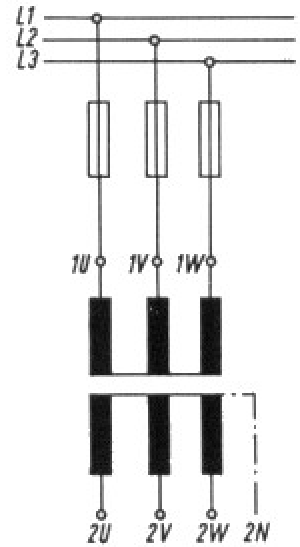
Configuration of a Three-phase Transformer

In principle, three-phase power can be transmitted using three, identical single-phase transformers whose primary and secondary windings are interconnected in star or delta mode. This principle is illustrated next.



However, this type of transformation requires too much material and space for medium and low powers. It is more practical and therefore more typical to use a three-phase transformer with a common iron body for all windings. Illustrated next is a three-phase transformer (in a star-star connection) equivalent to the illustration above and possessing a three-limb core (left), as well as the corresponding circuit diagram (right).





Illustrated next as an example is a three-phase oil-core transformer. The transformer oil in this design serves firstly for insulation, but also for cooling. For proper dispersal of generated heat, the oil vessel's thermal dissipation surface is enlarged by being furnished with cooling fins. To allow the oil filling to expand as the load and, consequently, the operating temperature increase, an oil expansion tank is positioned above the vessel and connected to it via a pipeline.

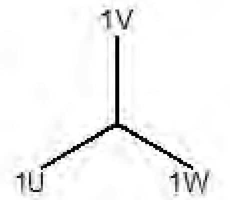
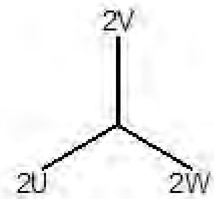
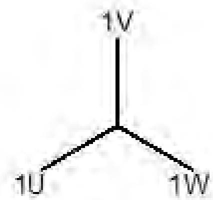
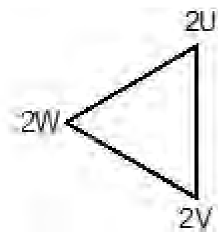
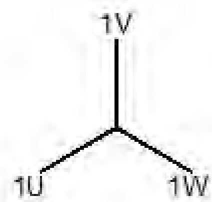
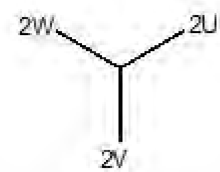
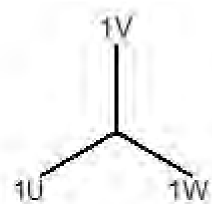
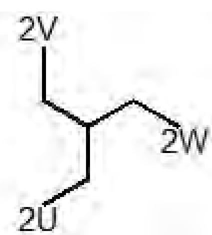
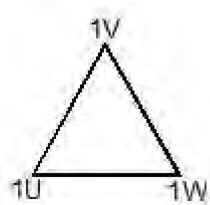
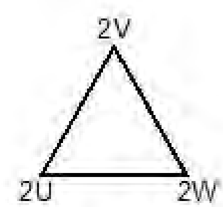
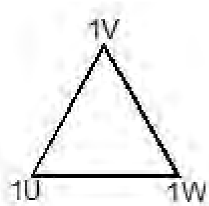
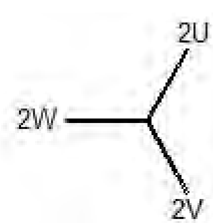
Circuit Types, Designations and Vector Groups

A three-phase transformer has three windings each on the primary and secondary sides. Each of these can be operated as part of a star or delta circuit. The following table summarizes the different types of circuit.

Circuit type	**Code letter**	
	Primary Winding	**Secondary Winding**
Star	Y	y
Delta	D	d
Zig-zag	Z	z
Open circuit	III	iii
Neutral point routed out	N	n

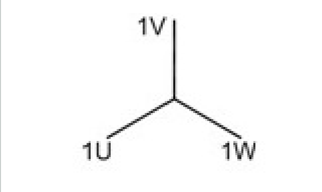
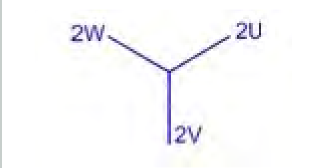
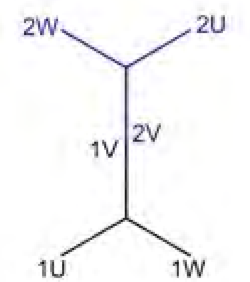
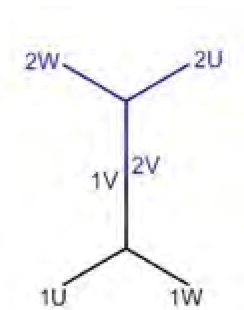
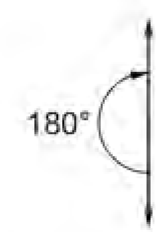
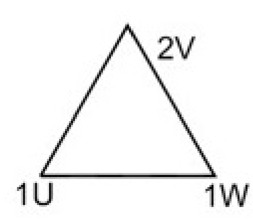
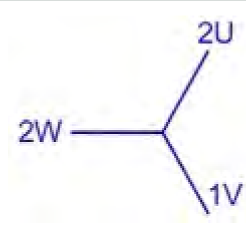
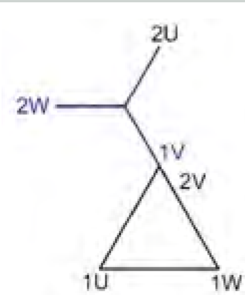
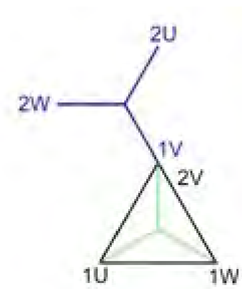
Depending on the circuit type, different vector groups arise on the primary and secondary sides. A number is appended to each vector group. This code number indicates the input voltage's phase shift with respect to the output voltage. Multiplying the code number by an angle of 30° results in the phase shift of the input and output voltages (example: code 5 means 5 x 30°, or a phase shift of 150°).

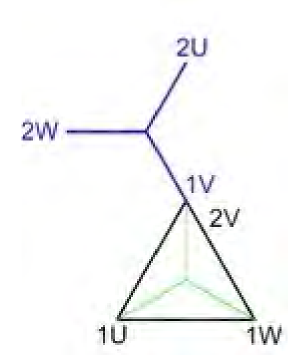
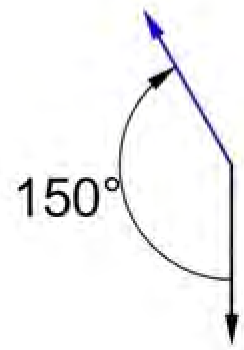
The following table provides examples of identifying different vector groups.

Vector group	Vector diagram	
	Primary side	Secondary side
Yy0		
Yd5		
Yy6		
Yz11		
Dd0		
Dy5		

Determining the Code Number

A code number can be determined for every vector group. This code number indicates the angle by which the voltage vector on the secondary side lags behind the one on the primary side. The code number does not specify the angle directly, but as a multiple of 30°. Code number 1 corresponds to an angle of 30°, code number 2 corresponds to 60°, etc. The next two examples again elucidate how to determine the code number.

The two vector diagrams show the primary and secondary voltages. To determine the shift, imagine an association between 1 V and 2 V.		
1 V and 2 V are linked here. Imagine two voltage vectors, one from 1 V to the neutral point, the other from 2 V to the neutral point.		
The angle between the two voltage vectors indicates the phase shift between the primary and secondary sides, in this case 180°. This results in the code number 6 (6 x 30° = 180°). The vector group accordingly receives the designation Yy6.		
The two vector diagrams show the primary and secondary voltages. To determine the shift, imagine an association between 1 V and 2 V.		
1 V and 2 V are linked here. To draw voltage vectors, a virtual neutral point must be plotted in the case of the delta circuit. This again results in two voltage vectors.		

The angle between the two voltage vectors indicates the phase shift between the primary and secondary sides, in this case 150°. This results in the code number 5 (5 x 30° = 150°). The vector group accordingly receives the designation Dy5.		

Transformer Protection

The protection needed by a transformer can be determined from its power rating. The sample calculation here makes use of the experiment board.

S_N = 100VA
Output voltage (V_{Str})= 3 x 230V

The following input current results for the star connection:

$$I_{Str} = \frac{S_N}{3V_{Str}} = \frac{100VA}{3 \cdot 230V} = 0{,}14A$$

Case 1: Vector Group Yy0 in the Case of a Balanced Load

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 5.
2. Turn on the transformer trainer.
3. Measure the output voltages and input currents, and enter the readings in the Table 3.
4. Turn off the transformer trainer.

The wiring diagram and set-up indicate the measuring instruments' wiring only for one phase. The instruments must be re-wired accordingly for the remaining phases.

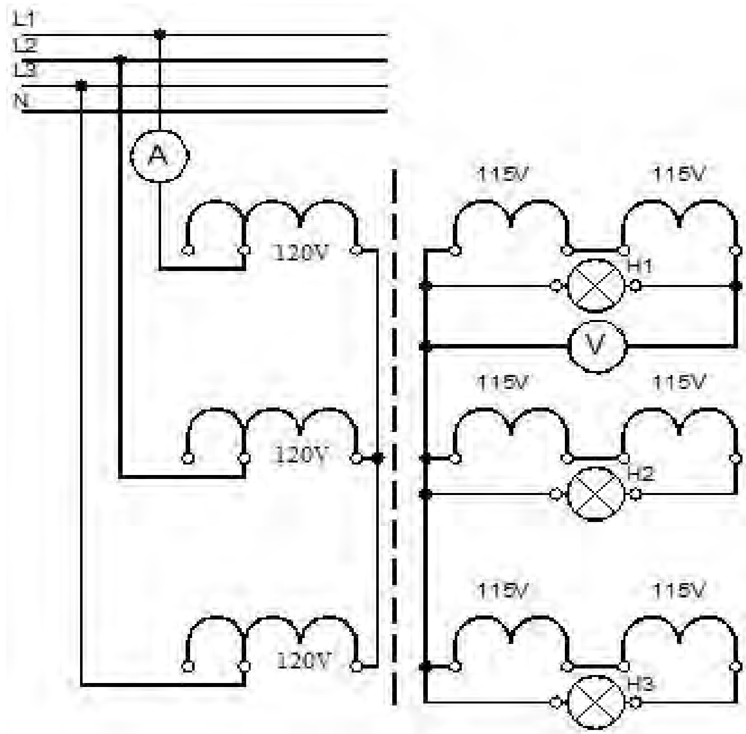


Figure 5:
Yy0 Balanced Load

Yy0 Balanced Load					
L1		L2		L3	
I_{1U} (mA)	V_{2U} (V)	I_{1V} (mA)	V_{2V} (V)	I_{1W} (mA)	V_{2W} (V)

Table 3:
Yy0 Balanced Load

Case 2: Vector Group Yy0 in the Case of an Unbalanced Load

A: Two Phases Load

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 6.
2. Turn on the transformer trainer.
3. Measure the output voltages and input currents, and enter the readings in the Table 4.
4. Turn off the transformer trainer.

> The wiring diagram and set-up indicate the measuring instruments' wiring only for one phase. The instruments must be re-wired accordingly for the remaining phases.

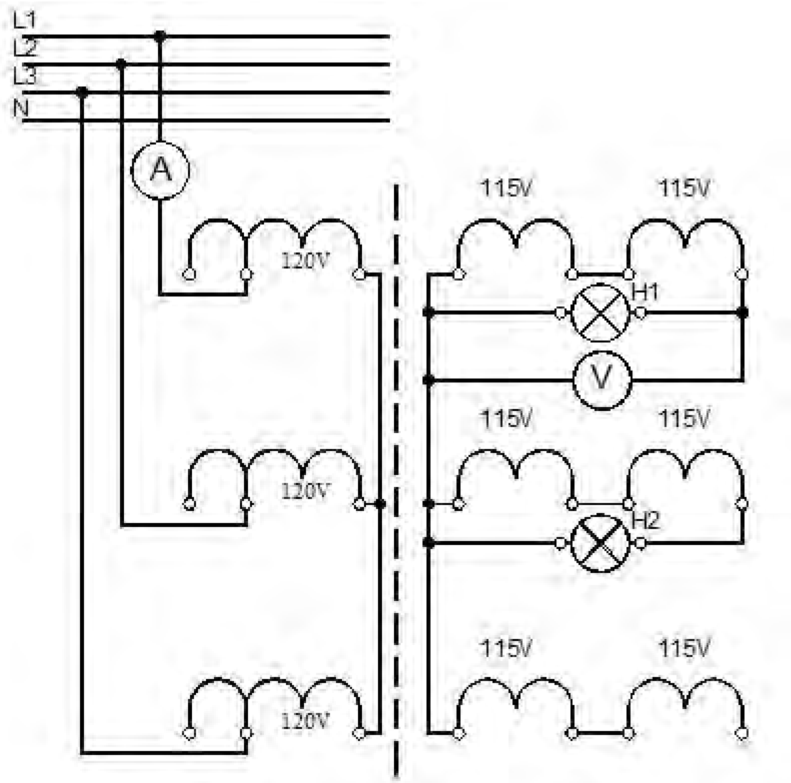


Figure 6:
Yy0 Unbalanced Load Two Phases

Yy0 Unbalanced Load Two Phases					
L1		L2		L3	
I_{1U} (mA)	V_{2U} (V)	I_{1V} (mA)	V_{2V} (V)	I_{1W} (mA)	V_{2W} (V)

Table 4:
Yy0 Unbalanced Load Two Phases

B: One Phase Load

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 7.
2. Turn on the transformer trainer.
3. Measure the output voltages and input currents, and enter the readings in the Table 5.
4. Turn off the transformer trainer.

The wiring diagram and set-up indicate the measuring instruments' wiring only for one phase. The instruments must be re-wired accordingly for the remaining phases.

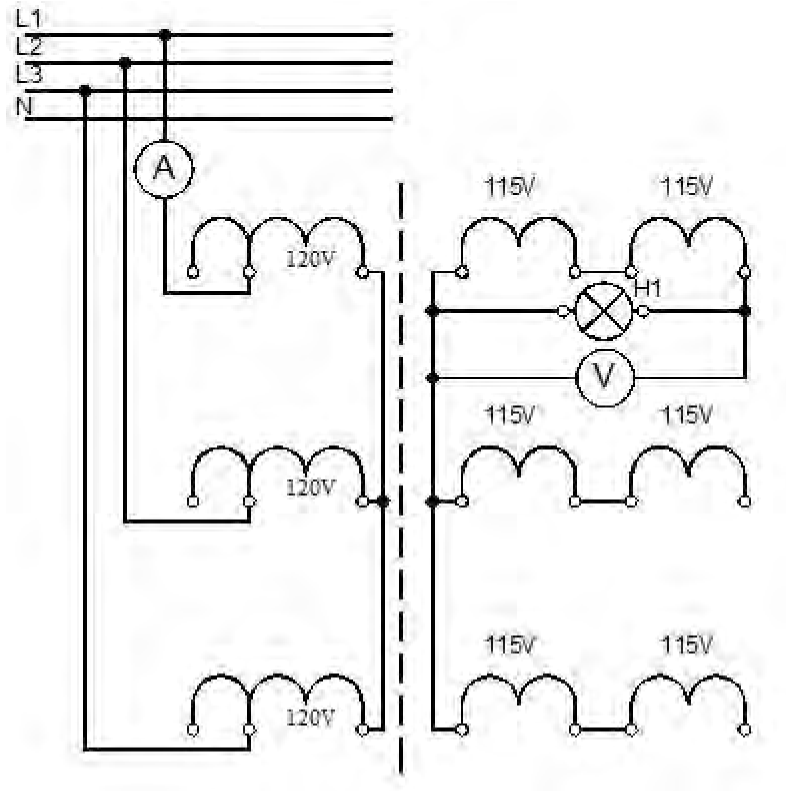


Figure 7:
Yy0 Unbalanced Load One Phase

Yy0 Unbalanced Load One Phase					
L1		L2		L3	
I_{1U} (mA)	V_{2U} (V)	I_{1V} (mA)	V_{2V} (V)	I_{1W} (mA)	V_{2W} (V)

Table 5:
Yy0 Unbalanced Load One Phase

Case 3: Vector Group YNy0 in the Case of an Unbalanced Load

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 8.
2. Turn on the transformer trainer.
3. Measure the output voltages and input currents, and enter the readings in the Table 6.
4. Turn off the transformer trainer.

The wiring diagram and set-up indicate the measuring instruments' wiring only for one phase. The instruments must be re-wired accordingly for the remaining phases.

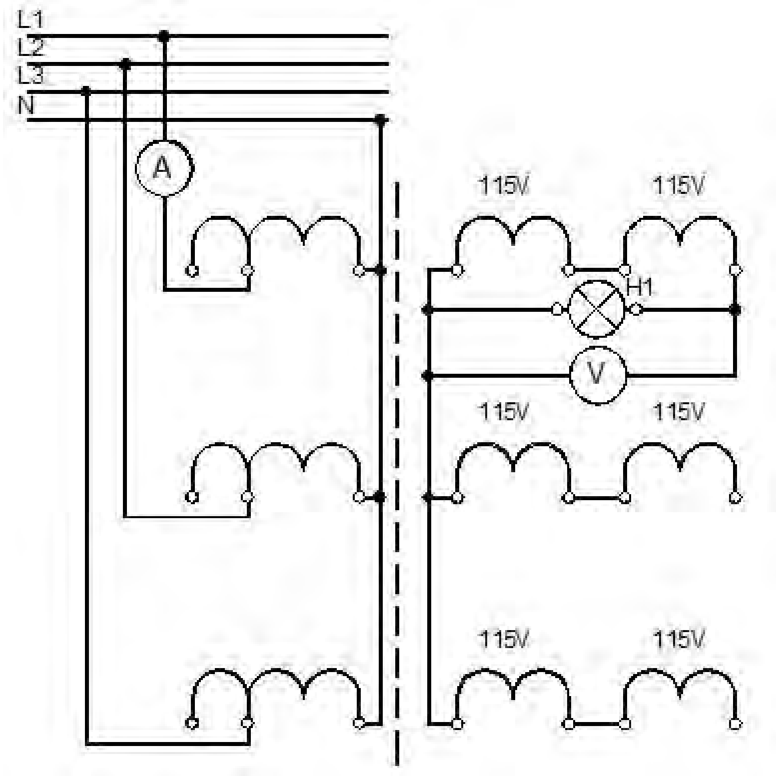


Figure 8:
YNy0 Unbalanced Load One Phase

YNy0 Unbalanced Load One Phase					
L1		L2		L3	
I_{1U} (mA)	V_{2U} (V)	I_{1V} (mA)	V_{2V} (V)	I_{1W} (mA)	V_{2W} (V)

Table 6:
YNy0 Unbalanced Load One Phase

Case 4: Vector Group Yz11 in the Case of a Balanced Load

The zig-zag circuit's transformation ratio differs from that of the other circuits. This is because the zig-zag circuit's two voltages must be geometrically added. This results in the following transformation ratio:

$$\ddot{v} = 2\frac{N_1}{\sqrt{3}N_2}$$

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 9.
2. Turn on the transformer trainer.
3. Measure the output voltages and input currents, and enter the readings in the Table 7.
4. Turn off the transformer trainer.

The wiring diagram and set-up indicate the measuring instruments' wiring only for one phase. The instruments must be re-wired accordingly for the remaining phases.

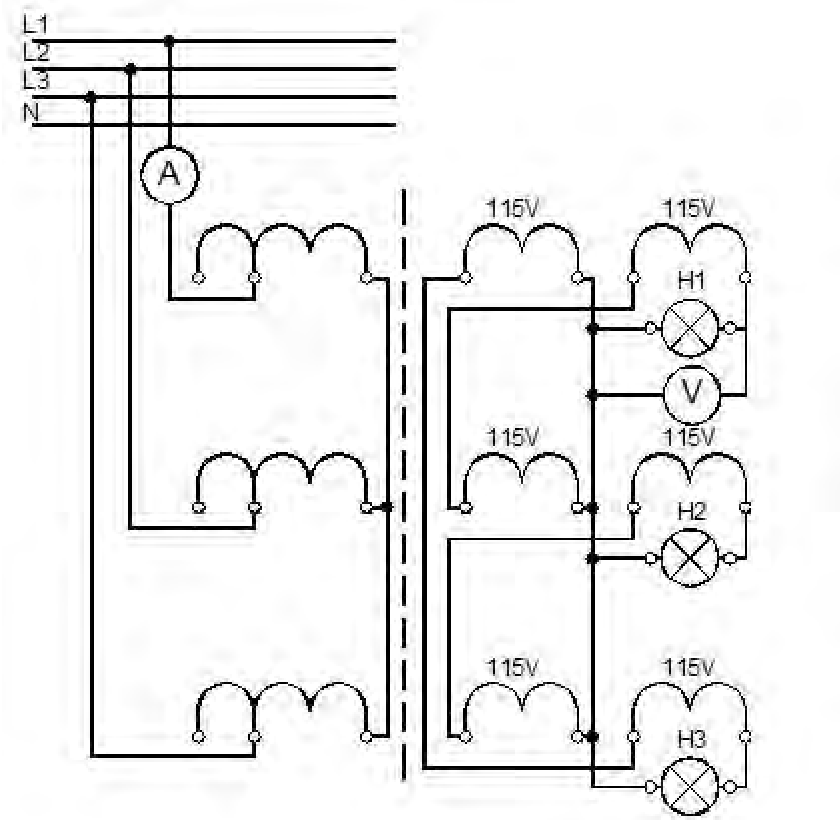


Figure 9:
Yz11 Balanced Load

Yz11 Balanced Load					
L1		L2		L3	
I_{1U} (mA)	V_{2U} (V)	I_{1V} (mA)	V_{2V} (V)	I_{1W} (mA)	V_{2W} (V)

Table 7:
Yz11 Balanced Load

Case 5: Vector Group Yz11 in the Case of an Unbalanced Load

A: Two Phases Load

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 10.
2. Turn on the transformer trainer.
3. Measure the output voltages and input currents, and enter the readings in the Table 8.
4. Turn off the transformer trainer.

The wiring diagram and set-up indicate the measuring instruments' wiring only for one phase. The instruments must be re-wired accordingly for the remaining phases.

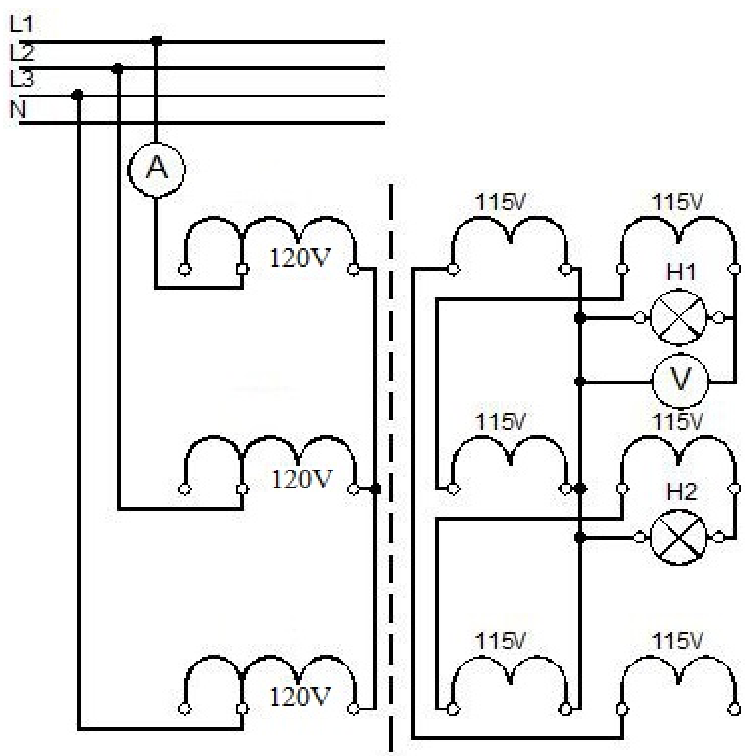


Figure 10:
Yz11 Unbalanced Load Two Phases

Yz11 Unbalanced Load Two Phases					
L1		L2		L3	
I_{1U} (mA)	V_{2U} (V)	I_{1V} (mA)	V_{2V} (V)	I_{1W} (mA)	V_{2W} (V)

Table 8:
Yz11 Unbalanced Load Two Phases

B: One Phase Load

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 11.
2. Turn on the transformer trainer.
3. Measure the output voltages and input currents, and enter the readings in the Table 9.
4. Turn off the transformer trainer.

The wiring diagram and set-up indicate the measuring instruments' wiring only for one phase. The instruments must be re-wired accordingly for the remaining phases.

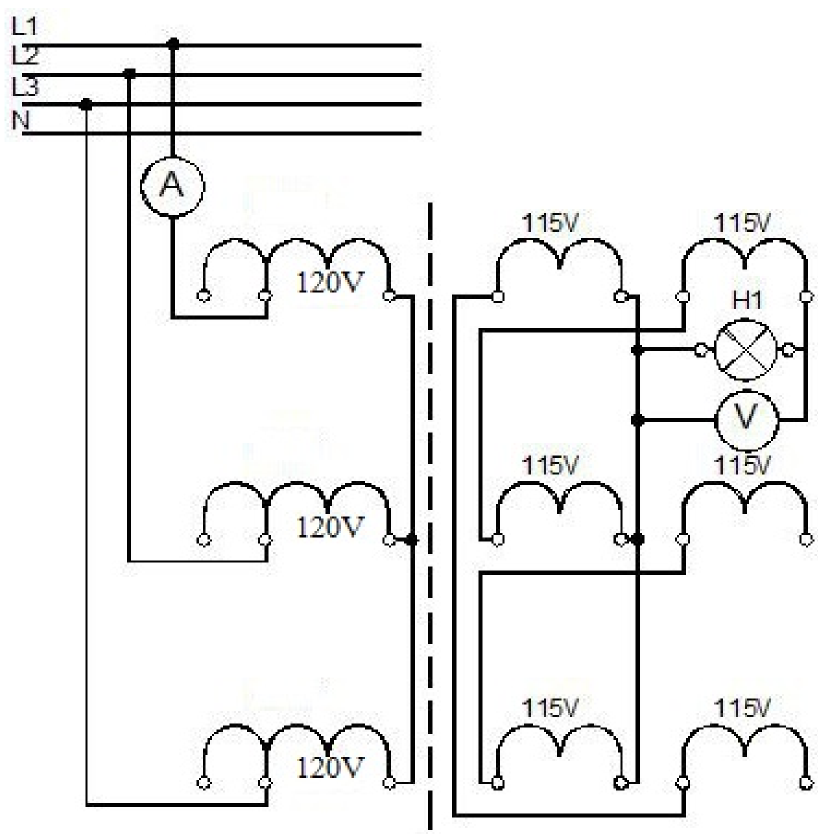


Figure 11:
Yz11 Unbalanced Load One Phase

Yz11 Unbalanced Load One Phase					
L1		L2		L3	
I_{1U} (mA)	V_{2U} (V)	I_{1V} (mA)	V_{2V} (V)	I_{1W} (mA)	V_{2W} (V)

Table 9:
Yz11 Unbalanced Load One Phase

Case 6: Vector Group Dy5 in the Case of a Balanced Load

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 11.
2. Turn on the transformer trainer.
3. Measure the output voltages and input currents, and enter the readings in the Table 10.
4. Turn off the transformer trainer.

> The wiring diagram and set-up indicate the measuring instruments' wiring only for one phase. The instruments must be re-wired accordingly for the remaining phases.

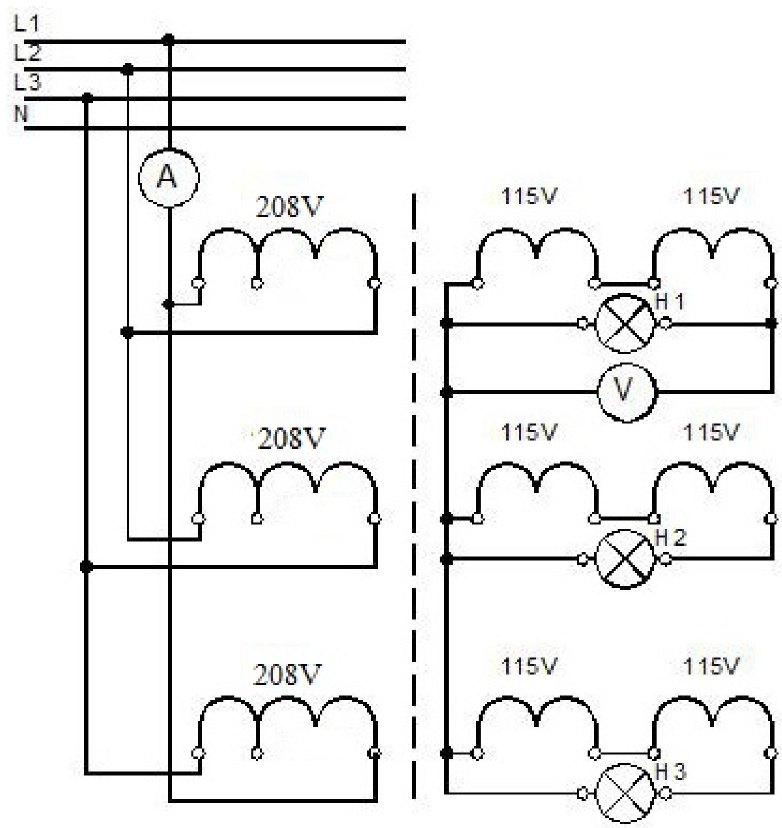


Figure 12:
Dy5 Balanced Load

Dy5 Balanced Load					
L1		L2		L3	
I_{1U} (mA)	V_{2U} (V)	I_{1V} (mA)	V_{2V} (V)	I_{1W} (mA)	V_{2W} (V)

Table 10:
Dy5 Balanced Load

Case 7: Vector Group Dy5 in the Case of an Unbalanced Load

A: Two Phases Load

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 13.
2. Turn on the transformer trainer.
3. Measure the output voltages and input currents, and enter the readings in the Table 11.
4. Turn off the transformer trainer.

The wiring diagram and set-up indicate the measuring instruments' wiring only for one phase. The instruments must be re-wired accordingly for the remaining phases.

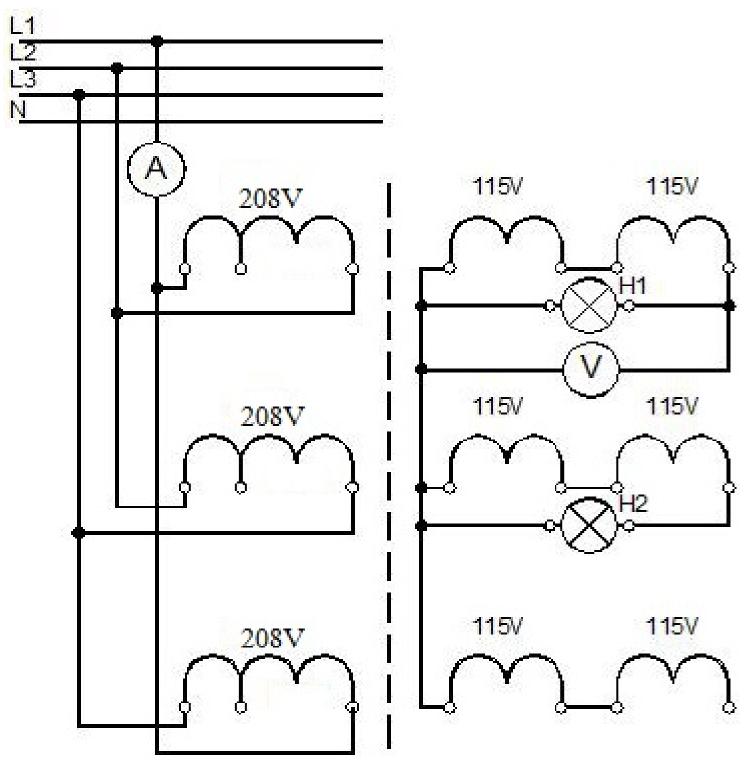


Figure 13:
Dy5 Unbalanced Load Two Phases

Dy5 Unbalanced Load Two Phases					
L1		L2		L3	
I_{1U} (mA)	V_{2U} (V)	I_{1V} (mA)	V_{2V} (V)	I_{1W} (mA)	V_{2W} (V)

Table 11:
Dy5 Unbalanced Load Two Phases

B: One Phase Load

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 14.
2. Turn on the transformer trainer.
3. Measure the output voltages and input currents, and enter the readings in the Table 12.
4. Turn off the transformer trainer.

> The wiring diagram and set-up indicate the measuring instruments' wiring only for one phase. The instruments must be re-wired accordingly for the remaining phases.

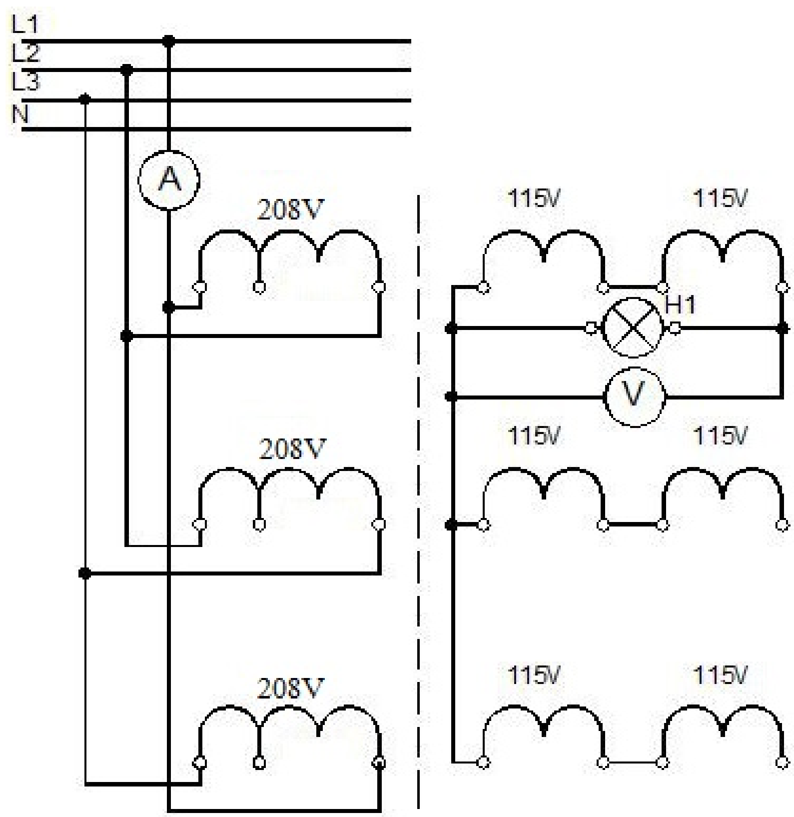


Figure 14:
Dy5 Unbalanced Load One Phase

Dy5 Unbalanced Load One Phase					
L1		L2		L3	
I_{1U} (mA)	V_{2U} (V)	I_{1V} (mA)	V_{2V} (V)	I_{1W} (mA)	V_{2W} (V)

Table 12:
Dy5 Unbalanced Load One Phase

Report Questions

1. How do the output voltages of the vector group Yy0 respond under the various loads?
2. How do the input currents of the vector group Yy0 respond under the various loads?
3. Is the vector group Yy0 suitable for operation with unbalanced loads? Why? Explain.
4. Compare the readings of the vector group YNy0 with those of the switch group not possessing a connected neutral point (vector group Yy0).
5. How do the output voltages of the vector group Yz11 respond under the various loads?
6. How do the input currents of the vector group Yz11 respond under the various loads?
7. Is the vector group Yz11 suitable for operation with unbalanced loads? Why? Explain.
8. How do the output voltages of the vector group Dy5 respond under the various loads?
9. How do the input currents of the vector group Dy5 respond under the various loads?
10. Is the vector group Dy5 suitable for operation with unbalanced loads? Why? Explain.
11. Where the vector group Dy5 is used?

eferences

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