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Transformers and electrical power transfer solutions

Electromagnetism 6 Supplying a remote observatory

Matching answers and examiner-style commentary

OCR A H556 | A-level physics | Module 6 | 43 marks

Specification points covered

6.3.3(f)(i) Laminated iron-core transformers; ideal turns, p.d. and current relationships.

6.3.3(f)(ii) Transformer investigations, including measurement, controls and graph analysis.

6.3.3(c), (d)(i) Lenz's and Faraday's laws. Apply prior circuit power, resistance and efficiency skills.

All a.c. voltages and currents quoted here are effective (r.m.s.) values. Use a resistive-load model with $P = VI$ and cable loss = I^2R. No phase or r.m.s. derivation is needed.

1 A cable to the observatory

A remote observatory requires 24.0 V a.c. and 60.0 W at its instruments. A receiving transformer steps down the voltage at the end of a long two-wire cable. The total resistance of the complete outgoing-and-return cable loop is 4.00 Ω.

For Questions 2 and 3, treat the receiving transformer as ideal. The supply is adjusted to maintain the specified voltage at its primary, after the cable drop.

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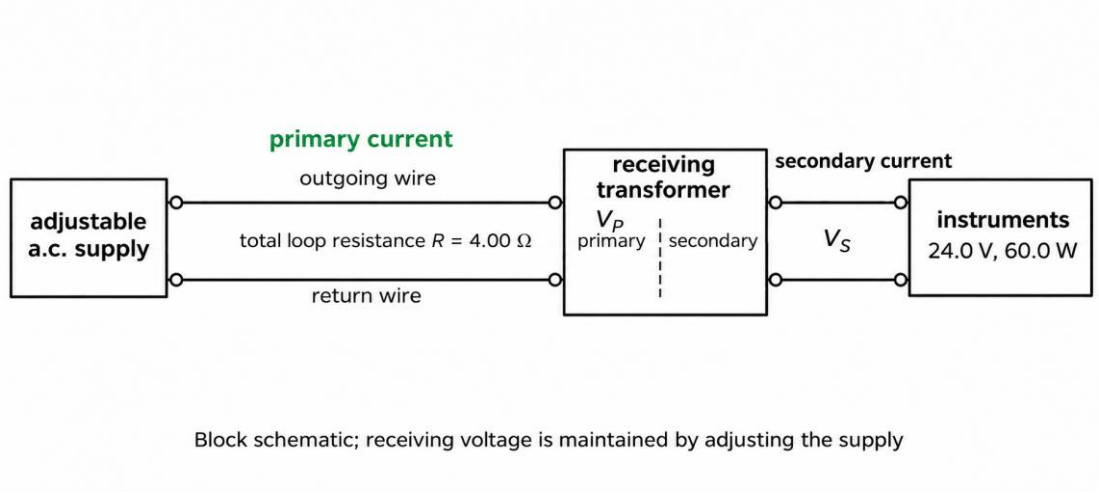


Figure 1 Supply, complete cable loop, receiving transformer and instruments; schematic

1(a) Explain how an alternating current in the primary coil produces an alternating p.d. across the separate secondary coil. **[3 marks]**

Step 1 Primary current produces changing magnetic flux

The alternating primary current produces a changing magnetic field and flux in the common core.

Step 2 The core links both coils

The changing core flux links the secondary turns, so the secondary flux linkage changes.

Step 3 Apply Faraday's law

An e.m.f. is induced in the secondary because its flux linkage changes. The direction of change reverses each half-cycle, so the induced p.d. is alternating. Charges do not pass from primary to secondary through the core.

Marking guidance Changing primary current/flux; shared flux links secondary; changing secondary linkage induces alternating e.m.f.

1(b) The core is made from insulated iron laminations. Explain the purposes of the iron and of the laminations. **[2 marks]**

The iron provides a path that links a large fraction of the primary flux with the secondary.

The insulated thin sheets restrict circulating eddy currents in the core, reducing unwanted heating and energy loss. Laminations do not electrically connect the two coils.

Marking guidance Improved shared flux linkage; laminations reduce eddy-current heating.

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2 An ideal receiving transformer

2(a) The receiving primary has 1000 turns and is maintained at 240 V. Calculate the secondary turns needed for 24.0 V. **[1 mark]**

$N_S/N_P = V_S/V_P$, so $N_S = 1000 \times 24.0/240 = 100$ turns. It is a step-down transformer.

Marking guidance 100 turns.

2(b) Calculate the current used by the 60.0 W instruments at 24.0 V. **[1 mark]**

$I_S = P/V_S = 60.0/24.0 = 2.50$ A.

Marking guidance 2.50 A.

2(c) Calculate the ideal primary current at 240 V. Explain why it is different from the secondary current. **[2 marks]**

Step 1 Use conservation of power for an ideal transformer

$V_P I_P = V_S I_S$, so $I_P = 60.0/240 = 0.250$ A.

Step 2 Interpret the current change

The higher primary voltage transfers the same power at a smaller current. Current is not conserved between the electrically separate primary and secondary circuits.

Marking guidance 0.250 A; same power at higher voltage requires lower current.

2(d) If the receiving primary is instead maintained at 48.0 V, what turns ratio $N_P : N_S$ is needed for the same 24.0 V instruments? **[1 mark]**

$N_P:N_S = V_P:V_S = 48.0:24.0 = 2:1$. The ratio is smaller than the 10:1 ratio used at 240 V.

Marking guidance 2:1.

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3 Choose the cable operating voltage

3(a) For an ideal transformer delivering 60.0 W, calculate the cable current when the maintained receiving-primary voltage is (i) 48.0 V and (ii) 240 V. **[2 marks]**

The cable carries the receiving-primary current, not the 2.50 A instrument current.

At 48.0 V: I = P/V = 60.0/48.0 = 1.25 A. At 240 V: I = 60.0/240 = 0.250 A.

Marking guidance 1.25 A; 0.250 A.

3(b) Calculate the power dissipated in the complete cable loop for each option. **[2 marks]**

Step 1 Use the total loop resistance once

$P_{loss} = I^2R$, with R = 4.00 Ω already including both wires.

Step 2 Compare the options

At 48.0 V: $P_{loss} = 1.25^2 \times 4.00 = 6.25$ W. At 240 V: $P_{loss} = 0.250^2 \times 4.00 = 0.250$ W.

Marking guidance 6.25 W; 0.250 W. Do not double the stated loop resistance.

3(c) Calculate the sending-end voltage needed to maintain each receiving-primary voltage. Include the cable p.d. drop. **[2 marks]**

Step 1 Find the cable drops

At 48.0 V: IR = 1.25 × 4.00 = 5.00 V. At 240 V: IR = 0.250 × 4.00 = 1.00 V.

Step 2 Add the drop to the required receiving voltage

Sending voltages are 48.0 + 5.00 = 53.0 V and 240 + 1.00 = 241 V. The receiving values are controlled; they are not the sending voltages.

Marking guidance 53.0 V; 241 V using the corresponding cable current.

3(d) Cable losses must be below 1.00 W. Select an option and explain why using the instrument current in I^2R would give the wrong answer. **[2 marks]**

Use the maintained 240 V receiving-primary option: its ideal cable loss is 0.250 W, below 1.00 W; the 48.0 V option loses 6.25 W.

The 2.50 A current flows in the separate 24.0 V secondary circuit. The cable carries the smaller primary current, so it must use that current in I^2R.

Marking guidance 240 V justified by both losses; correct distinction between primary cable and secondary load currents.

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4 Account for a real transformer

Use the stated effective readings and resistive/unity-power-factor model. Do not introduce a phase correction.

4(a) The real receiving transformer is 90.0% efficient while delivering 60.0 W. Calculate its electrical input power. **[1 mark]**

$\eta = P_{out}/P_{in}$, so $P_{in} = 60.0/0.900 = 66.6667$ W ≈ 66.7 W. The input is larger than the useful output.

Marking guidance 66.7 W.

4(b) The receiving-primary voltage is still maintained at 240 V. Calculate the cable current for this real transformer. **[1 mark]**

$I_{line} = P_{in}/V_P = 66.6667/240 = 0.277778$ A ≈ 0.278 A, under the stated P = VI model.

Marking guidance 0.278 A using transformer input power.

4(c) Calculate the new cable loss and the efficiency from electrical power at the cable's sending end to useful power at the instruments. Exclude all losses before that sending end. **[3 marks]**

Step 1 Calculate the cable loss using the unrounded current

$P_{cable} = 0.277778^2 \times 4.00 = 0.308642$ W.

Step 2 Find the power entering the complete cable-plus-transformer system

$P_{send} = P_{in} + P_{cable} = 66.6667 + 0.308642 = 66.9753$ W.

Step 3 Use the defined system boundary

$\eta_{system} = 60.0/66.9753 = 0.89585 = 89.6\%$. Cable loss is additional to transformer loss; neither is counted twice.

Marking guidance Cable loss about 0.309 W; sending power about 67.0 W including both losses; whole-system efficiency 89.6%.

4(d) A pupil uses $I_P/I_S = N_S/N_P$ to claim that the real primary current must still be 0.250 A. Explain the problem with this argument. **[2 marks]**

That current relationship assumes an ideal transformer with no power loss. This real transformer needs 66.7 W input to provide 60.0 W output, so its primary current is greater than the ideal value.

At the maintained 240 V the appropriate current is 0.278 A under the given power model. A nominal turns/p.d. relationship does not remove the extra input power needed for losses.

Marking guidance Ideal-current relation identified as inappropriate; losses require greater input power and primary current.

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5 Test the turns and voltage relationship

The secondary p.d. is measured with a high-input-resistance a.c. voltmeter and no separate load. Sketch a circuit in the space beside your method if useful.

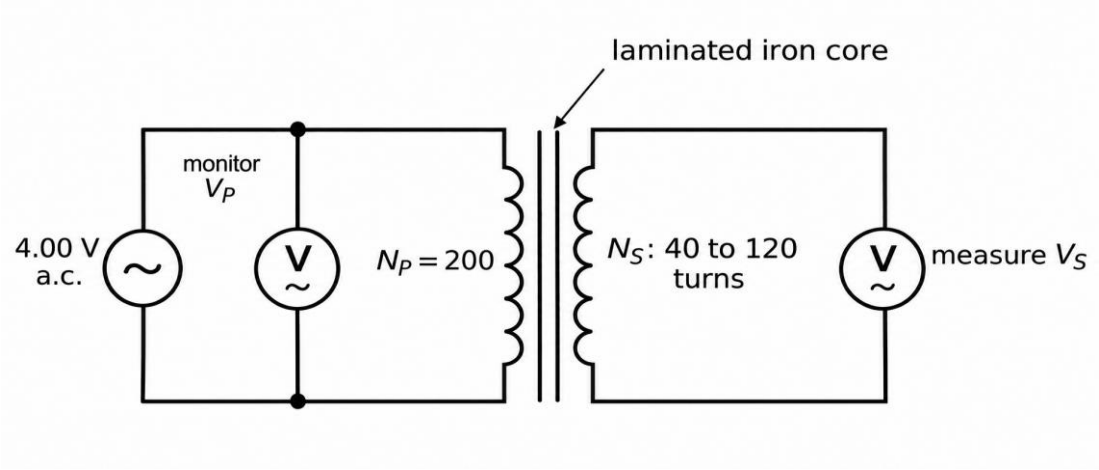


Figure 2 Parallel voltage measurements on electrically separate windings

5(a) A low-voltage prototype has $N_P = 200$ and an isolated 4.00 V a.c. supply. The secondary can use 40, 60, 80, 100 or 120 turns. Predict the no-load secondary voltage for each turn count. **[2 marks]**

$V_S = V_P N_S / N_P = 4.00 N_S / 200 = 0.0200 N_S$.

For N_S = 40, 60, 80, 100, 120, the predicted voltages are 0.800, 1.20, 1.60, 2.00, 2.40 V respectively. These are no-load readings, not secondary currents.

Marking guidance Correct proportional relationship; all five predictions.

5(b) State what graph should test this prediction and give the expected gradient and intercept, including units where appropriate. **[2 marks]**

Plot V_S in V on the vertical axis against N_S on the horizontal axis. The expected straight-line gradient is V_P/N_P = 0.0200 V per turn and the intercept is zero.

This prediction assumes the primary voltage remains 4.00 V and the same core and primary winding are used.

Marking guidance Axes and straight line through origin; gradient 0.0200 V per turn.

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5 Test the turns and voltage relationship Extended response

5(c) Write a six-mark-style method to test this relationship. Include a labelled circuit description or sketch, controls, a range and repeats, graph analysis and a justified uncertainty/improvement. Use only the isolated low-voltage a.c. prototype. **[6 marks]**

Step 1 Connect and control the apparatus

Connect the isolated low-voltage a.c. supply to the 200-turn primary. Connect an a.c. voltmeter in parallel across the primary and a separate high-input-resistance a.c. voltmeter across the tapped secondary. The two windings share a closed laminated iron core but have no electrical connection.

Keep the primary turns, core assembly and supply frequency fixed. Monitor the primary p.d. and adjust it to 4.00 V for every reading; the source setting alone may not guarantee that value. Keep the secondary effectively unloaded by the high-resistance meter.

Step 2 Collect enough readings

Use all five secondary turn counts from 40 to 120. Record N_S, V_P and V_S; repeat each measurement and calculate a mean V_S. Choose an a.c. voltage range with suitable resolution for about 0.8–2.4 V.

Step 3 Analyse and evaluate

Plot mean V_S against N_S. A straight line consistent with the origin and gradient consistent with 0.0200 V per turn supports the prediction. Use a best-fit gradient over a large triangle rather than one pair of readings.

Use meter resolution/quoted accuracy and repeat scatter to judge voltage uncertainty; monitor primary-voltage drift as a possible systematic effect. A wider safe turn/voltage range, better resolution or a more stable source can reduce the relevant fractional uncertainty. Repeating alone does not remove calibration error.

Assessing 5(c) Best-fit marking guidance

Level 3 (5–6): a connected, feasible low-voltage a.c. method with monitored controls, range and repeats AND appropriate graph/gradient analysis and a relevant justified uncertainty or improvement The argument is clear, linked and scientifically sound.

Level 2 (3–4): a sound account of one strand with limited treatment of the other, or some relevant detail in both; links or evaluation are incomplete.

Level 1 (1–2): limited creditworthy method or analysis, presented as fragments with little connection. 0: no creditworthy response.

Use best fit, then the quality within the level. The exemplar is indicative, not a six-keyword checklist; accept other workable, justified approaches.

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6 State what is kept constant

6(a) Why does a steady d.c. primary current not give a sustained secondary e.m.f.? Explain what may happen briefly when the d.c. is switched on or off. **[2 marks]**

A steady current gives steady core flux and therefore no rate of change of secondary flux linkage, so there is no sustained induced e.m.f.

At switching, the current and flux change briefly; a transient secondary e.m.f. can occur. A d.c. supply is not a suitable substitute for the alternating supply in the turns experiment.

Marking guidance No changing linkage with steady d.c.; brief switching transient linked to changing flux.

6(b) In a separate ideal test, keep $V_P = 4.00$ V, $N_P = 200$ and the same 40.0 Ω secondary resistor. Calculate I_S for $N_S = 40$, 80 and 120, and state how I_S depends on N_S under these conditions. **[2 marks]**

Step 1 Find the secondary voltages

$V_S = 4.00N_S/200$ gives 0.800, 1.60 and 2.40 V.

Step 2 Keep the load resistance fixed

$I_S = V_S/R$ gives 0.0200, 0.0400 and 0.0600 A. Here I_S is directly proportional to N_S, because $V_S \propto N_S$ and R is fixed. Output power is not fixed.

Marking guidance All three currents; direct proportionality justified using the fixed resistor.

6(c) Now keep output power fixed at 0.0800 W by changing the secondary resistance for each turn count. The primary is still ideal at 4.00 V with 200 turns. Calculate I_S for $N_S = 40$, 80 and 120. Explain why the trend differs from 6(b). **[2 marks]**

Step 1 Use the same turns-dependent secondary voltages

$V_S = 0.800$, 1.60, 2.40 V.

Step 2 Keep output power fixed instead of resistance

$I_S = P/V_S$ gives 0.100, 0.0500 and 0.0333 A. Here $I_S \propto 1/N_S$ because P is fixed and $V_S \propto N_S$.

The required resistances are 8.00, 32.0 and 72.0 Ω, so this is a different load condition from the fixed 40.0 Ω test. In this ideal fixed-power case $I_P = 0.0800/4.00 = 0.0200$ A throughout.

Marking guidance All three currents; inverse trend correctly attributed to fixed power and changing load.

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6(d) Improve this explanation: “The core carries charge into the secondary and creates extra power when the voltage goes up.” **[2 marks]**

The core links the coils magnetically; charge does not flow through it from primary to secondary. A changing secondary flux linkage induces the e.m.f.

A transformer transfers energy supplied to the primary. In an ideal step-up transformer the current decreases so power is unchanged; in a real one useful output power is less than input power.

Marking guidance Magnetic linkage rather than charge transfer; power conservation with inverse ideal voltage/current change.

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