SOLUTIONS MANUAL FOR

PRINCIPLES OF ANALOG ELECTRONICS

by

Giovanni Saggio

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CHAPTER 9 – DIODE CIRCUITS

Exercise 1

A half-wave rectifer as in Figure 9.1 has an input voltage signal $v_s = V_M\,sin(\omega t)$.

Assuming ideal diode ($V_\gamma = 0$*, zero resistance in forward biasing condition), calculate the following:*

- The average output voltage $V_{o,DC}$ across the resistor
- The average current $I_{o,DC}$ flowing throught the resistor
- The RMS value of the output voltage $V_{o,RMS}$ across the resistor
- The RMS value of the current $I_{o,RMS}$ flowing throught the resistor
- The form factor $F_{F,1s}$
- The ripple factor γ

ANSWER

The output voltage function of the half-wave rectifier is represented in Figure 1

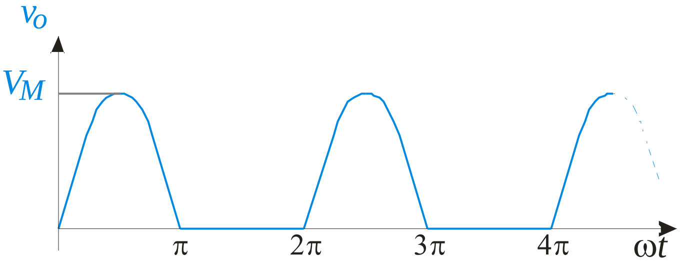

Figure 1: output voltage function of the half-wave rectifier

To obtain the requested values, each time we can start with the respective definitions.
So, the average output (DC) voltage will be:

$$V_{o,DC} = \frac{1}{\pi}\int_0^{\pi} v_s d(\omega t) = \frac{1}{\pi}\int_0^{\pi} V_M\,sin(\omega t)\,d(\omega t) = \frac{V_M}{\pi}$$

The average output current:

$$I_{o,DC} = \frac{V_{DC}}{R} = \frac{V_M}{\pi R}$$

The same result can be equivalently obtained considering that this circuit does not produce any phase shift, so that the current can be written as $i(\omega t) = I_M\,sin(\omega t)$). So:

$$I_{o,DC} = \frac{1}{2\pi}\int_0^{2\pi} I_M\, sin(\omega t)\, d(\omega t) = \frac{1}{2\pi}\left[\int_0^{\pi} I_M\, sin(\omega t)\, d(\omega t) + \int_{\pi}^{2\pi} 0 d(\omega t)\right] = \frac{I_M}{2\pi}[-cos(\omega t)]_0^{\pi} + 0$$

$$= \frac{I_M}{2\pi} — 1 - 1 = \frac{I_M}{\pi}$$

To determine the RMS value of the output voltage, we have:

$$V_{o,RMS} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} v_S^2 d(\omega t)} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} V_M^2\, sin^2(\omega t)\, d(\omega t)} == \sqrt{\frac{V_M^2}{2\pi}\int_0^{\pi}\left[\frac{1 - cos(2\omega t)}{2}\right] d(\omega t)}$$

$$= V_M\sqrt{\frac{1}{2\pi}\left[\frac{\omega t}{2} - \frac{sin(2\omega t)}{4}\right]_0^{\pi}} = V_M\sqrt{\frac{1}{2\pi}\left[\frac{\pi}{2}\right]} = \frac{V_M}{2}$$

The RMS value of the output current:

$$I_{o,RMS} = \frac{V_{o,RMS}}{R} = \frac{V_M}{2R}$$

The same expression can be equivalently found as:

$$I_{o,RMS} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} I_M^2\, sin^2(\omega t)\, d(\omega t)} = \sqrt{\frac{1}{2\pi} I_M^2 \frac{\pi}{2}} = \frac{I_M}{2}$$

which corresponds to the RMS value of the total current, that is the sum of DC and AC components.

Now, the RMS value of the only AC component, $I_{r,RMS}$, that is the RMS value of the ripple, can be determined starting from the definition applied to the term $(i - I_{DC})$:

$$I_{r,RMS} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} (i - I_{DC})^2 d(\omega t)} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} [i^2 - 2iI_{DC} + I_{DC}^2] d(\omega t)}$$

but

$$\sqrt{\frac{1}{2\pi}\int_0^{2\pi} i^2 d(\omega t)} = I_{RMS}^2$$

$$\frac{1}{2\pi}\int_0^{2\pi} i d(\omega t) = I_{DC}$$

so

$$I_{r,RMS} = \sqrt{I_{RMS}^2 - 2I_{o,DC}^2 + I_{o,DC}^2} = \sqrt{I_{RMS}^2 - I_{o,DC}^2}$$

The form factor is defined as the RMS and average ratio, $F_F \stackrel{\text{def}}{=} \frac{V_{o,RMS}}{V_{o,DC}} = \frac{I_{o,RMS}}{I_{o,DC}}$, so:

$$F_{F,1s} = \frac{0{,}5V_M}{0{,}32V_M} \cong 1{,}57$$

Let's see now how we can calculate the ripple. Since the pure AC voltage component is defined as the sinusoidal wave $v_o(= V_M\,sin(\omega t)\ which\ is \neq 0\ for\ 0 < \omega t < \pi\ and\ zero\ elsewhere)$ apart from its DC component $V_{o,DC}$, that is $v_o - V_{o,DC}$, we have:

$$V_{r,RMS} = \sqrt{\frac{1}{\pi}\int_0^{\pi}\left[V_M\,sin(\omega t) - V_{o,DC}\right]^2 d(\omega t)} = \sqrt{\frac{1}{\pi}\int_0^{\pi}\left[V_M^2\,sin^2(\omega t) + V_{o,DC}^2 - 2V_{o,DC}V_M\,sin(\omega t)\right]d(\omega t)}$$

but we already saw that

$$V_{oRMS} = \sqrt{\frac{1}{\pi}\int_0^{\pi} V_M^2\,sin^2(\omega t)\,d(\omega t)}$$

therefore replacing

$$V_{r,RMS} = \sqrt{\left(V_{o,RMS} - V_{o,DC}\right)^2}$$

as a consequence the ripple of the half-wave rectifier is

$$r = \frac{V_{r,RMS}}{V_{o,DC}} = \frac{\sqrt{\left(V_{o,RMS} - V_{o,DC}\right)^2}}{V_{o,DC}} = \sqrt{\left(\frac{V_{o,RMS}}{V_{o,DC}}\right)^2 - 1} = \sqrt{\left(\frac{V_M/2}{V_M/\pi}\right)^2 - 1} = 1.21$$

The same result can be obtained solving respect to the current rather than to the voltage:

$$r = \frac{I_{r,RMS}}{I_{o,DC}} = \frac{\sqrt{I_{o,RMS}^2 - I_{DC}^2}}{I_{o,DC}} = \sqrt{\left(\frac{I_{o,RMS}}{I_{o,DC}}\right)^2 - 1} = \sqrt{\frac{\frac{I_M}{2}}{\frac{I_M}{\pi}} - 1} = 1.21$$

Summing

$V_{o,DC} = \frac{V_M}{\pi}$; $I_{o,DC} = \frac{V_M}{\pi R}$; $V_{o,RMS} = \frac{V_M}{2}$; $I_{o,RMS} = \frac{V_M}{2R}$; $F_{F,1s} \cong 1{,}57$; $\gamma = 1.21$

Exercise 2

A half-wave rectifier circuit, as in Figure 9.1, has an input sinusoidal voltage source $v_s = V_M\,sin(\omega t)$, with $V_M = 10V$, $R = 500\Omega$. Assuming an ideal diode ($V_\gamma = 0$, zero resistance in forward biasing conditions) calculate the following:

- *The maximum current value I_M*
- *DC component of current I_{DC}*
- *RMS value of current I_{RMS}*
- *DC component of voltage in output V_{DC}*
- *DC component of power delivered to the load $P_{o,DC}$*
- *Power value supplied by the source P_s*
- *The ripple value γ*

ANSWER

The maximum current value is

$$I_M = \frac{V_M}{R} = 20mA$$

its DC component

$$I_{DC} = \frac{1}{\pi R}\int_0^{\pi} v_s d(\omega t) = \frac{V_M}{\pi R} = 6.3mA$$

and its RMS value

$$I_{RMS} = \sqrt{\frac{1}{\pi R}\int_0^{\pi} v_s^2 d(\omega t)} = \frac{V_M}{2R} = 10mA$$

The DC component of the output voltage

$$V_{DC} = RI_{DC} = 6.3V$$

The power from the source and the power to the load are respectively

$$P_s = RI_{RMS}^2 = 100mW$$

$$P_{o,DC} = RI_{DC}^2 = 39.7mW$$

Observation

To determine the electric power we consider the absolute values of current and/or voltage when DC but RMS values when AC.
For the current exercise the output voltage is a periodic one so that to calculate the electric power we should utilize the RMS values but, on the contrary, it is commonly adopted the average ones. This is because the final scope of the circuit is to furnish a constant voltage across the load.

Finally, the ripple value

$$\gamma = \sqrt{\left(\frac{I_{RMS}}{I_{DC}}\right)^2 - 1} \cong 1.23$$

Summarizing:
$I_M = 20mA$; $I_{DC} = 6.3mA$; $I_{RMS} = 10mA$; $V_{DC} = 6.3V$; $P_{o,DC} = 39.7\text{m}W$; $P_s = 100mW$; $\gamma \cong 1.23$

Exercise 3

A half-wave rectifier has an input stage with a transformer, turns ratio $n = 20{:}\,1$, *and a load resistance* $R = 50\Omega$*. The input voltage source has a RMS value of* $V_{s,RMS} = 220V$ *(Figure 9.23).*

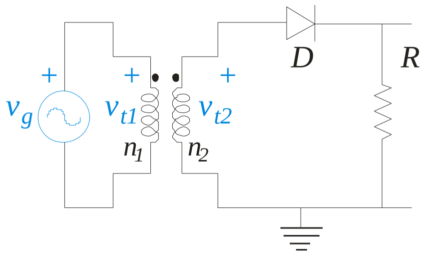

Figure 9.23: half-wave rectifier with a transformer as the first stage

Let's determine the following:

- DC component of voltage in output $V_{o,DC}$
- DC component of current in output $I_{o,DC}$
- RMS value of voltage in output $V_{o,RMS}$
- RMS value of current in output $I_{o,RMS}$
- the ripple value γ

ANSWER

Across the secondary coil there is a RMS voltage equal to $\frac{220}{10} = 22V$, so that the maximum voltage across the half-wave rectifier's input port is

$$V_M = \sqrt{2} * 22 \cong 31.12V$$

According to the previous exercises we know that the DC output voltage can be written as

$$V_{o,DC} = \frac{V_M}{\pi} \cong 9.9V$$

and the output current

$$I_{o,DC} = \frac{V_{o,DC}}{R} \cong 198mA$$

while their RMS values

$$V_{o,RMS} = \frac{V_M}{2} \cong 15.56V$$

$$I_{o,RMS} = \frac{V_{o,RMS}}{R} \cong 0.31A$$

Summarizing

$V_{o,DC} \cong 9.9V$; $I_{o,DC} \cong 198mA$; $V_{o,RMS} \cong 15.56V$; $I_{o,RMS} \cong 0.31A$; $\gamma \cong 1.21$.

Observation

Note that this ripple value is quite high, so the half-wave rectifier is a poor AC to DC converter.

Exercise 4

A half-wave rectifier network is used as a battery charger (Figure 9.24).

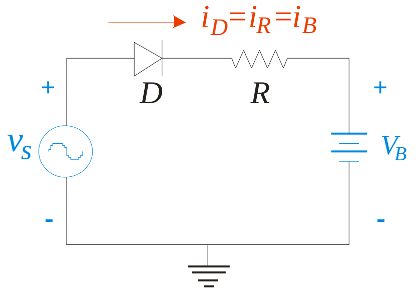

Figure 9.24: a simple battery charger by means of a half-wave rectifier

When the source voltage is higher than that of the battery, the current flows from the source to the battery, which charges. Reverse conditions are not possible because of the presence of the diode. Assuming a voltage source of $v_s = 150\, sin(\omega t)$, an ideal diode ($V_\gamma = 0$ and a short-circuit in forward bias condition, an open-circuit in reverse bias conditions), and a $75V$ battery with a charge current of $750mA$, determine the resistance value of the resistor R.

ANSWER

The charging current can flow only when the diode is in “active” mode (ON), and since $V_B = 75V$ this corresponds to the a-b, a’-b’, a”-b”,.. intervals of v_s, in green color of Figure 9.24b.

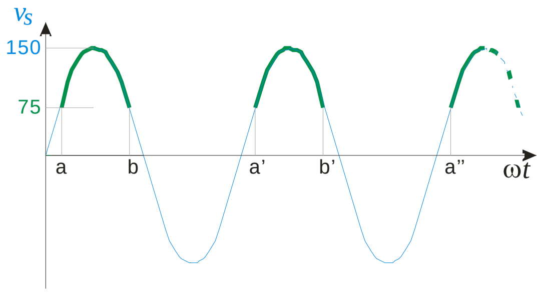

Figure 9.24b: the current flows through the diode during the green part of vs

To determine the value of ωt corresponding to the point a, b, a’, b’, a’’ etc.., we can impose

$$150\, sin(\omega t) = 75$$

so

$$\omega t = \begin{cases} {}^{1}/_{6}\,\pi \\ {}^{5}/_{6}\,\pi \end{cases}$$

When the current differs from zero, it is equal to

$$i = \frac{v_s - 75}{R} = \frac{150\sin(\omega t) - 75}{R}$$

but we have to consider the DC value of the current which charges the battery

$$I_{DC} = \frac{1}{2\pi}\int_{1/_6\pi}^{5/_6\pi} \frac{150\sin(\omega t) - 75}{R} d(\omega t) = \frac{1}{2\pi R}[-150\cos(\omega t) - 75\omega t]_{1/_6\pi}^{5/_6\pi}$$

$$= \frac{1}{2\pi R}\left[-150\left(-\frac{\sqrt{3}}{2}\right) - 75\frac{5}{6}\pi + 150\frac{\sqrt{3}}{2} + \frac{75}{6}\pi\right]$$

Now, according to the request, we impose $I_{DC} = 750mA$, obtaining

$$R \cong 22\Omega$$

Observations

A *battery's capacity* $C\ [Ah]$ refers to the stored electric charge that can be delivered in an ammount of time at room temperature ($77°F$ or $25°C$). A $500[Ah]$ rated battery can supply $1A$ for $500h$, or $5A$ for $100h$, or $10A$ for $50h$, or $100A$ for $5h$. But the capacity is not the perfect parameter to give a real measure for a battery, because it depends on the discharge conditions: the current's value (not necessary constant), the value of the voltage, the temperature, the discharging rate.

The *C-rate* (or *charge-rate* or *hourly-rate*) of a battery specifies the discharge rate, as a multiple of the *capacity*. So, for example, a battery with a capacity $C = 1.5[Ah]$ and a $C/10$ rate, deliveres $\frac{1.5}{10} = 0.15[A]$; A $1C$ rate means that the battery discharges entirely in $1[h]$. This is similar for the *E-rate* but referred to the power, not the current.

Exercise 5

A battery with $C = 1200mAh$, $V_B = 5V$, *and* $C - rate = 10$, *must be charged by a half-wave rectifier with a transformer at its input port, having a turns ratio* $n = 15$. *The AC voltage source* $v_s = V_M \sin(\omega t)$ *has a RMS voltage of* $V_{s,RMS} = 220V$ *(Figure 9.25).*

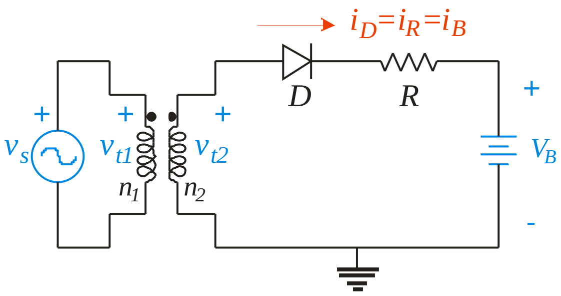

Figure 9.25: Half-wave rectifier with a transformer at its input port

Assuming a diode with $V_\gamma = 0.74V$, *calculate the following:*

- The average charging current, I_B
- The value of the resistance R necessary to limit the current
- The RMS current flowing throught the battery, I_{RMS}