Impact of Transistor Parameters on the On-state and Off-state Impedances

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ARTICLE INFO	ABSTRACT
Keywords: *Transistor's Parameters,* *On-State Impedance,* *Off-State Impedance,* *Affecting Factors.*	*Impedance parameters, also known as Z-parameters or network parameters, are used to describe the behavior of linear electrical networks. They relate the voltage and current at the terminals of a network element or a network of interconnected elements. The transistor element is widely used in electronic design applications. It is known that the transistor element has very important functions in electronic designs for industrial purposes. The aim of this study is to obtain formulas for on-state and off-state impedance in common emitter transistor circuits. For this purpose, the obtained formulas were investigated using MATLAB software. Obtained findings and parameters affecting on-state and off-state impedance states are presented with the help of graphics. In the off state, a transistor is typically in a non-conducting state, and the collector current is very close to zero. Therefore, in the off state of a transistor, the open-circuit collector current is considered negligible, or effectively zero. Whereas, in the on state of a transistor, the emitter-base voltage typically depends on the specific operating conditions and the transistor biassing. The voltage between the emitter and base terminals can vary based on the applied input voltage, load conditions, and the transistor's characteristics.*

I. Introduction

The first transistor was made by scientists of Bell Laboratory in 1984. With the expansion of using in various equipment such as microprocessors, microcontrollers, rail transit, wind power generation devices and aeronautics, identifying the factors affecting their operation has become particularly important [1-3]. Bipolar junction transistors (BJT) are three terminals' devices made of semi-conducting materials and can act as an insulator or as a conductor by applying a small signal voltage. The ability of transistors to change between these two states allows for two basic functions, which are called "switching" (digital electronics) or "amplification" (analog electronics). In this situation, BJTs have the ability to work in three different areas (active, saturation and cut-off). BJTs have some merits like low turn-on loss, proper durability and low maintenance price which make them a good choice for using in analogue circuits [4]. According to Webster effect, the main disadvantage of BJT is low switching speed [5]. In forward mode, base and emitter is short circuit and collector put a forward voltage in accordance with emitter. In this regard, with applying 5V voltage on collector, positive conducting is appeared. In common emitter connection, the input signal is connected between the base and emitter gates of the transistor, while the corresponding output signal is taken from the collector and emitter gates. This type of connection is one of the most commonly used connections for transistor-based amplifiers, which provides the highest current and

power gain among the other three types of BJT. This structure has a low input impedance because the input is connected to a forward bias and has a high output impedance because it includes a reverse-biased connection. The main contributions of this paper are as follows:

- Designing a mathematical model to determine the impedance level of the transistor in on-state and off-state
- Evaluation of the impact of different parameters on transistor impedances
- Comparison of the sensitivity level of transistor impedance to ambient temperature variations

In order to explain the proposed approach and present the obtained results, the structure of this article continues as follows:

In the second part, at first, explanations about bipolar junctions' transistors are given, and then the equations of the common-emitter transistor operation are presented. In the third part, the mathematical modeling of the transistor's impedances in on-state and off-state is presented and the method of extracting the equations has been investigated. In the next part, the impedance sensitivities with respect to variation in temperature, V_C, α_I and α_N are calculated and the obtained results are explained by related figures. In the last part, a summary of the approach and the obtained results are presented.
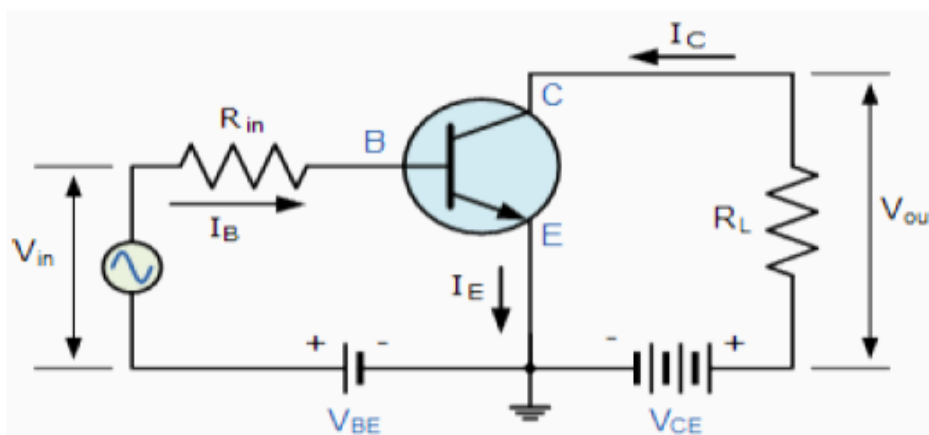
II.   Common-emitter BJT transistors

If two individual signal diodes are connected back-to-back, this will produce two PN-junctions connected in series and share a common P or N terminal. The combination of these two diodes produces a two junction with three terminals devices which represent the basic Bipolar junction transistor (BJT). So, we can define a Bipolar Junction Transistor as a component consists of two PN-junctions producing three connecting terminals namely emitter, collector and base. In common-emitter (CE) configuration, V_{BE} and I_B are the input parameters and V_{CE} and I_C represent the output parameters [6] (Fig. 1). For CE configuration which is the most commonly used circuit in the applications of transistor-based amplifiers, the emitter current (I_E) is given by the Equ. (1). Also, the current gain (α) is the ratio between I_C and I_E (Equ. (2)) and its value is always less than unity. Another current gain (β) is defined as the ratio between I_C and I_B, which will be a quite larger. According to these equations, if any small change occurs in the I_B, then I_C will change in a much larger way, so CE is controlled by the small changes of the current flowing in the base. This configuration is operating as inverter amplifier because the output voltage is 180° out-of-phase with the input voltage. A Bipolar transistor can be used for switching operations with two different states (cut-oof and saturation). In other words, if it works in the saturation state, it will act like a closed switch "on-state" and when is operates in the cut-off state, it behaves like an open switch "off-state".

$$I_E = I_C + I_B \tag{1}$$
$$\alpha = \frac{I_C}{I_E} \tag{2}$$
$$\beta = \frac{I_C}{I_B} \tag{3}$$

I_E : Emitter current
I_C : Collector current
I_B : Base current
α, β : Current gains

Fig. 1: Schematic of common-emitter mode of BJT transistor [7]

Both PNP and NPN transistors can be used as switches. In our project, a NPN Transistor in CE mode will be used. In this status, I_E and I_C currents are determined with Equs. (4) and (5), respectively.

$$I_E = -\frac{I_{E0}}{1-\alpha_N\alpha_I}\left(e^{qV_{EB}/kT}-1\right) + \alpha_N\frac{I_{C0}}{1-\alpha_N\alpha_I}\left(e^{qV_{CB}/kT}-1\right) \tag{4}$$

$$I_C = \alpha_N\frac{I_{E0}}{1-\alpha_N\alpha_I}\left(e^{qV_{EB}/kT}-1\right) - \frac{I_{C0}}{1-\alpha_N\alpha_I}\left(e^{qV_{CB}/kT}-1\right) \tag{5}$$

I_{E0} : Emitter current
I_{C0} : Collector current
α_N : Base current
α_I : Current gains
q : Charge of electron
V_{EB} : Emitter-base voltage
k : Boltzman's constant
T : Temperature

III.   Mathematical Modeling

The input/output impedances of a transistor depends of its applied configuration and related changes according to the operation state. In the other side, on-state and off-state impedances of a transistor affect the performance and the stability of the circuit. Therefore, these impedances should be taken into account when designing circuits consist of transistors.

3.1 On-state impedance

In this situation, the transistor is operating in the saturation mode ($V_{CE} < 0.7$(v)) and I_B is increased until I_C is independent of it [8] (Fig. 2). and consist of the following characteristics:

*   The input and base are connected to V_{CC}.
*   The V_{BE} is greater than the cut-in voltage (normally 0.7 V).
*   Both the BC and BE junctions are forward biased.
*   The transistor operates as a closed switch (on-state).
*   The maximum amount of I_C can be achieved by maximizing the I_B current.
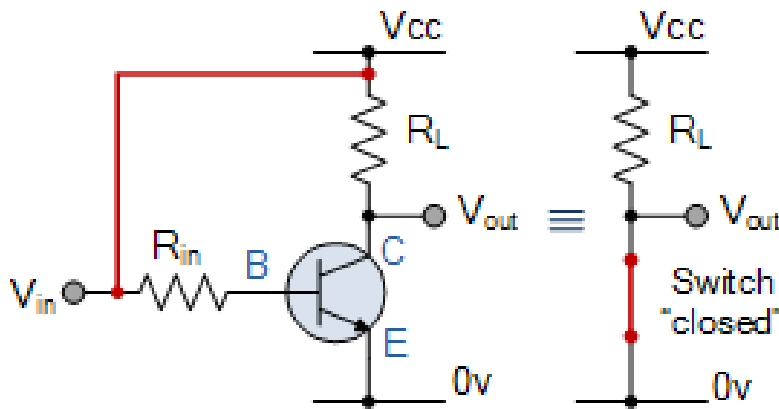

Fig. 2: NPN Transistor in saturation mode [9]

In this regard, Since both junctions are forward biased, I_C is determined according to Equ. (6). Then, with some manipulations like as Equ. (7), V_{CB} can be calculated as Equ. (8). Finally, the on-statee impedance can be defined as Equ. (9).

$$I_C = \alpha_N\left(\alpha_I\frac{I_{C0}}{1-\alpha_N\alpha_I}e^{qV_{CB}/kT} - I_E\right) - \frac{I_{C0}}{1-\alpha_N\alpha_I}e^{qV_{CB}/kT} \tag{6}$$

$$I_C + \alpha_N I_E = e^{qV_{CB}/kT}\left(\alpha_N\alpha_I\frac{I_{C0}}{1-\alpha_N\alpha_I} - \frac{I_{C0}}{1-\alpha_N\alpha_I}\right) \tag{7}$$

$$= e^{qV_{CB}/kT}\left[-I_{C0}\left(\frac{1-\alpha_N\alpha_I}{1-\alpha_N\alpha_I}\right)\right] = -I_{C0}e^{qV_{CB}/kT}$$

$$\frac{qV_{CB}}{kT} = \ln[-\frac{I_C + \alpha_N I_E}{I_{C0}}] \tag{8}$$

$$Z\_On = \frac{V_c}{I_c} = \frac{kT}{qI_C}\ln[\frac{I_{C0}}{I_C + \alpha_N I_E}] \tag{9}$$

3.2 Off-state impedance
In this state, the transistor operates in the Cut-Off mode (off-state) and the following characteristics will be verified (Fig. 3):

- The input I_B is grounded ($I_B = 0$).
- The V_{BE} is less than the cut-in voltage (e.g. $V_{BE} < 0.7$ V).
- Both BC and BE junctions are reverse biased.
- The transistor acts like open switch (off-state)
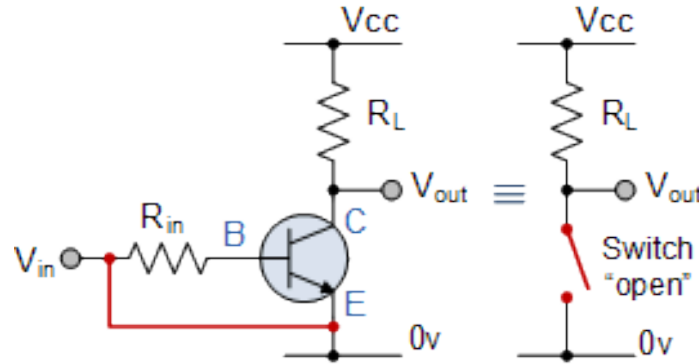- The V_{CE} is in the maximum condition, $V_{out} = V_{CC}$ and $I_C = 0$.

Fig. 3: NPN Transistor in cut-off mode [9]

In this scenario, since $V_{EB} << \frac{KT}{q}$ and $V_{CB} << \frac{KT}{q}$, the I_C and I_E are calculated as Equs. (10) and (11), respectively. Then, V_{EB} and V_{CB} are defined as Equs. (12) and (13), respectively. Finally, the off-state impedance is calculated as Equ. (14).

$$I_C = -\alpha_N \frac{I_{E0}}{1 - \alpha_N \alpha_I} + \frac{I_{C0}}{1 - \alpha_N \alpha_I} = \frac{I_{C0} - \alpha_N I_{E0}}{1 - \alpha_N \alpha_I} \tag{10}$$

$$I_E = -\frac{I_{E0}}{1 - \alpha_N \alpha_I} e^{qV_{EB}/kT} - \alpha_I (I_C - \alpha_N \frac{I_{E0}}{1 - \alpha_N \alpha_I} e^{qV_{EB}/kT}) \tag{11}$$

$$V_{EB} = \frac{kT}{q} \ln(-\frac{I_E + \alpha_I I_C}{I_{E0}}) \tag{12}$$

$$V_{CB} = \frac{kT}{q} \ln(-\frac{I_C + \alpha_N I_E}{I_{C0}}) \tag{13}$$

$$Z\_Off = \frac{V_c}{I_c} = \frac{V_c(1 - \alpha_N \alpha_I)}{I_{C0} - \alpha_N I_{E0}} \tag{14}$$

IV.   Simulation results

In this paper, an NPN Transistor will be operated as a switch. The specification of used NPN transistor is given in the Table 1. In this regard, when $V_{IN} > 0.7$ V, the transistor acts as a short circuit and IC is flowing through the transistor. Similarly, when not enough voltage is applied at the input, transistor operates in cut-off mode and acts as an open-circuit.

Table 1: Characteristics of NPN transistor

Parameter	Value	Unit	Parameter	Value	Unit
α_I	100	-	q	1.1×10^{-19}	c
α_N	100	-	k	1.38×10^{-23}	$kg.m^2k^{-1}s^{-2}$
R_B	50	KΩ	V_{CB}	5	Volt
R_C	0.7	KΩ	V_{BE}	0.65	Volt
I_{E0}	0.1	mA	I_{C0}	100	mA

4.1 On-state impedance variations vs. α_I
The variation of on-state impedance accordance to α_I is shown in Fig. (1). In this condition, value of α_I has changed from 50 to 300 and the value of on-state impedance has increased from 0.25 $\mu\Omega$ to 1.47 $\mu\Omega$. As it is clear

in the Fig. (4), the resistance of the transistor has increased. In other words, for each unit increase in the value of α_I, the resistance of the transistor increases 0.005 $\mu\Omega$.
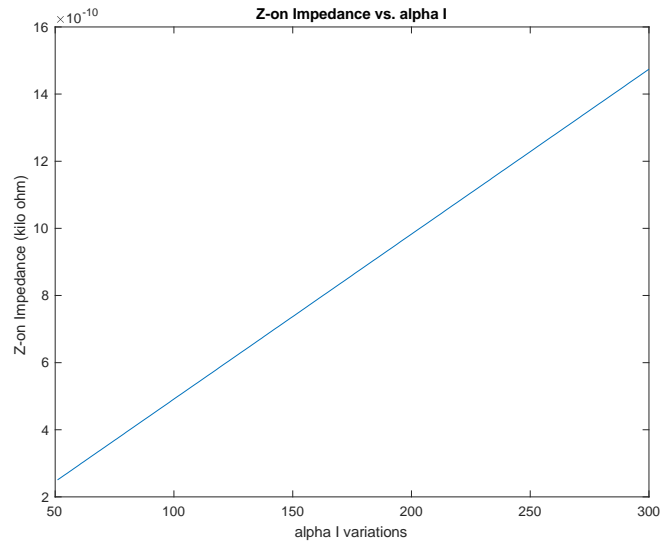

Fig. 4: Variation of Z-on vs. α_I

4.2 On-state impedance variations vs. α_N

The variation of on-state impedance accordance to α_N is shown in Fig. (5). In this condition, value of α_N has changed from 50 to 300 and the value of on-state impedance has increased from 0.238 $\mu\Omega$ to 1.90 $\mu\Omega$. The increase in the resistance of the transistor is greater than the increasing caused by the variation in the α_I coefficient. In fact, the resistance of the transistor in the on-state mode is more sensitive to changes in the α_N coefficient.
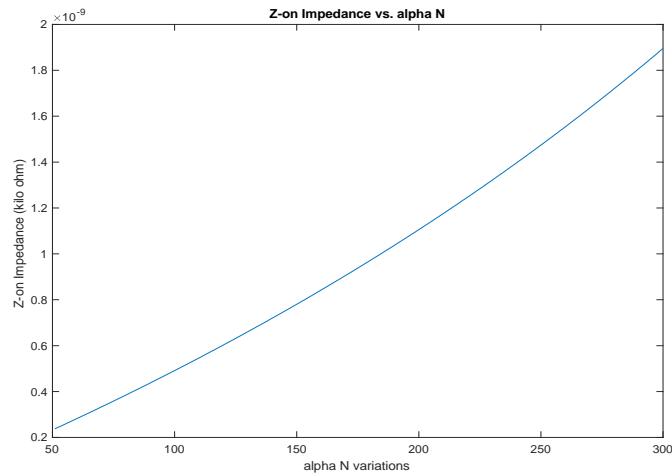

Fig. 5: Variation of Z-on vs. α_N

4.3 On-state impedance variations vs. temperature

In this section, the impedance variations of the transistor in the active state with increasing temperature have been evaluated. The temperature increased from 5° to 45° degrees and the amount of changes in such conditions is presented in Fig. (6). As can be seen, the amount of changes can be ignored and in fact the increase in temperature cannot have a significant effect on the operation of the transistor in the on-state.
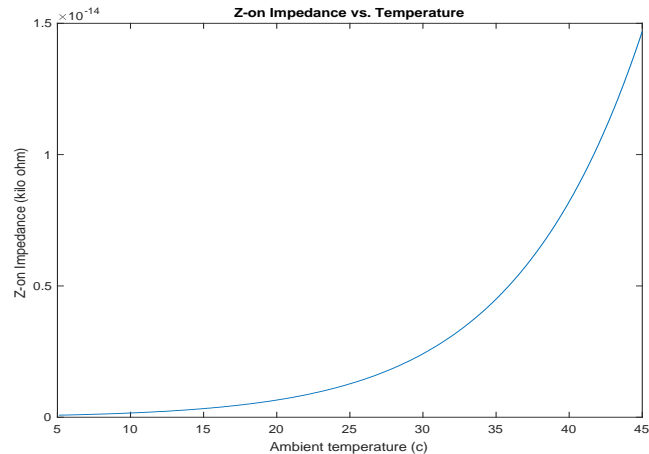
Fig. 6: Variation of Z-on vs. Temperature

4.4 Off-state impedance variations vs. α_I

The variation of off-state impedance accordance to α_I is shown in Fig. (7). In this condition, value of α_I has changed from 50 to 300 and the value of off-state impedance has increased from 113 **kΩ** to 667 **kΩ** . In this regard, increasing the coefficient α_I causes the resistance value of the transistor to increase up to 5 times. This means that by changing this parameter, it is possible to significantly increase the amount of impedance in the cut-off mode.
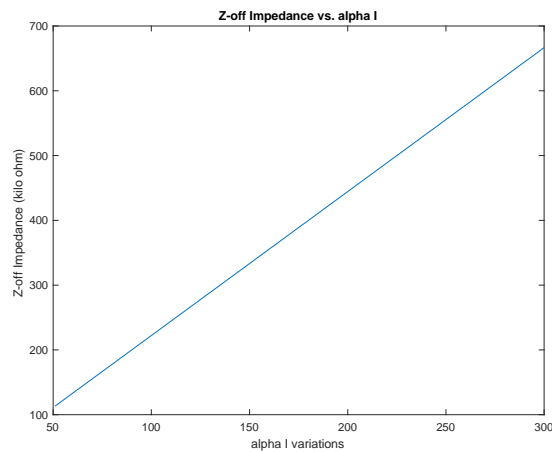

Fig. 7: Variation of Z-off vs. α_I

4.5 Off-state impedance variations vs. α_N

The variation of off-state impedance accordance to α_N is shown in Fig. (8). In this condition, value of α_N has changed from 50 to 300 and the value of off-state impedance has increased from 107 **kΩ** to 857 **kΩ**.
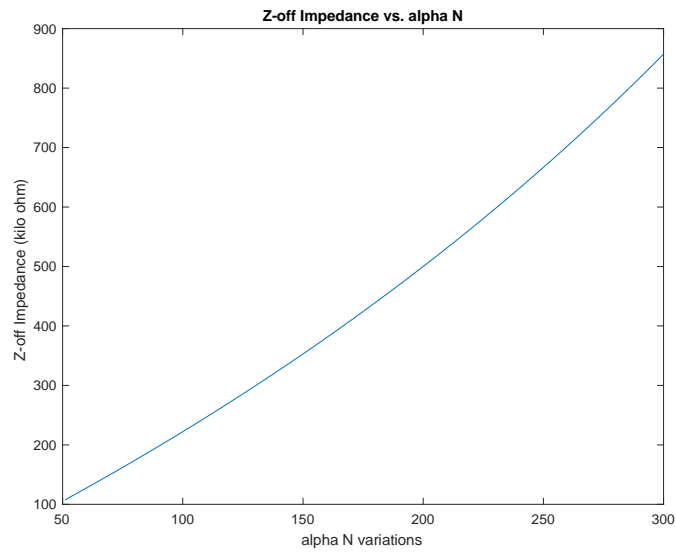
Fig. 8: Variation of Z-off vs. α_N

4.6 Off-state impedance variations vs. temperature

In this section, the impedance variations of the transistor in the active state with increasing temperature have been evaluated. The temperature increased from 5° to 45° degrees and the amount of changes in such conditions is presented in Fig. (9). The obtained result shows that the impedance of the transistor in the off-state is not a depend on the temperature of the ambient and its increase/decrease cannot significantly change its value.
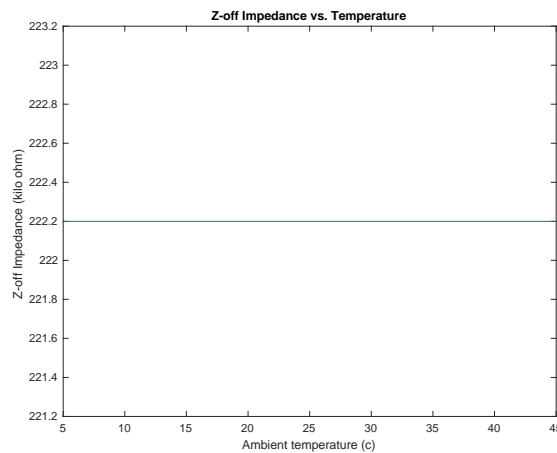

Fig. 9: Variation of Z-off vs. Temperature

4.7 On-state impedance variations vs. Vc

In the last scenario, the effect of changes of Vc on the off-state impedance has been investigated. As it is clear in the Fig. (10), as the collector voltage increases from 1 (v) to 20 (v), the impedance also increases from 110 **kΩ** to 2200 **kΩ**. As shown in Fig. (10), the maximum value of the impedance variation in the off-state mode is related to the changes of collector voltage. In fact, with the increase of Vc, the impedance value of the transistor increases more than 20 times. This shows that by carefully controlling the value of it, the impedance range of the transistor can be controlled in a wide range.
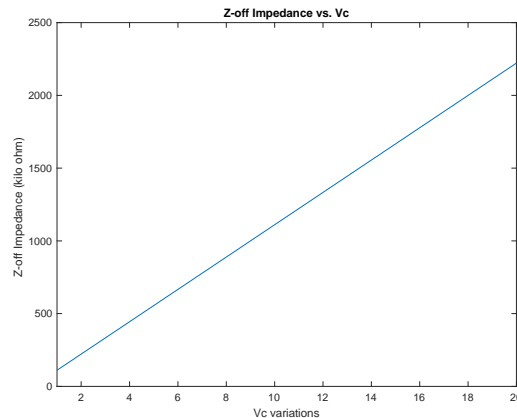
Fig. 10: Variation of Z-on vs. Vc

V. Conclusion

With the expansion of electronic equipment in nowadays, using of transistors has also increased significantly. In this situation, BJT transistors are still used as a vital element in the electronics industry due to their advantages such as low turn-on loss, proper durability and low maintenance price. In this situation, evaluating the effect of various factors on the impedance in on-state and off-state of transistors can be very helpful to better control of their performance. For this project, the common-emitter transistor is used. After obtaining the mathematical model, the effectiveness of different parameters on impedance has been studied. According to obtained results, for on-state impedance the most effective factors belong to α_N, α_I and temperature, respectively. In other side, for off-state mode the most effective factors are collector voltage, α_N and α_I, respectively. It should be noted that the highest sensitivity obtained in the proposed approach is related to variation of V_C. So, with exact regulation of V_C, the off-impedance of transistor can be controlled properly.

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