Time-dependent Electron Transport throughoutQuantum Dot in the Absence ofNonresonanceChannel

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Abstract

In this work , we study the transport properties of a quantum dot in the presence of electromagnetic fields , in the absence ofnonresonance channel , by using the time-evolution operator technique . The frequency and amplitude of the electromagnetic fields ,that applied to leads and the quantum dot , are taken into consideration . The equations of motion for this system are derived and solved numerically in the wide-band limit approximation . The quantum dot charge , the total number of electrons on the left lead and the curretnt flowing from the lift lead are calculated and investigated for wide range of parameters .

1. Introduction

Time-dependent phenomena in nanostructures are of growing interest for understanding and controlling their dynamic behavior . Electronic transport in mesoscopic systems has been at the focus of experimental and theoretical interest during the last decade due to recent development in fabrication of small electronic devices and their interesting equilibrium and non-equilibrium properties. Especially , interesting in the transport properties of a quantum dot (QD) under the influence of external time-dependent fields [Qing Sun etal.,1997]. The frequency signals may be applied to a QD and the time-dependent fields may modify the tunneling current .New effects have been observed and theoretically described, e.g. photon-assisted tunneling through small quantum dots with well-resolved discrete energy states [T. H. Oosterkamp et al.,1997;Qing-feng et al.1997;Qing-feng et al.,1998], photon-electron pumps [C.A. Stafford et al.,1996;L.P. Kouwenhoven et al.,1991] .

In this work, we consider the transport properties of a quantum dot (QD) under the influence of external electromagnetic fields. We consider the simplest case for the quantum dot with single energy level, without the electron-electron Coulomb interaction, coupled to two leads (right and left) in the presence of external electromagnetic fields which act (under the adiabatic approximation) on all the parts of the considered system[B.R. Bulka et al.,2001]. We describe the dynamical evolution of the charge localized on the QD and the current flowing through the system in terms of the time evolution operator[M. Tsukada et al.,1995]. We consider the influence of the electromagnetic field on electron transport through the QD without additional tunneling channel .

All the evolution operator elements that required for the calculations of the QD charge or electron current are obtained by solving the corresponding sets of the integro-differential equations numerically. The system of equations of motion is treated (to be more simple) by using wide band approximation then these equations are solved numerically using six order Runge – Kutta method.

2. The Model Hamiltonian

The system under ,we study, consists of a Quantum Dot sandwiched between two leads, the first,(left lead), is the source of electrons and the other lead,(right lead), is a reservoir of electrons drain (see fig. (1)).The interactions between left lead and the quantum dot and quantum dot and right lead are taken into account ,while we neglect the left lead-right lead interaction .

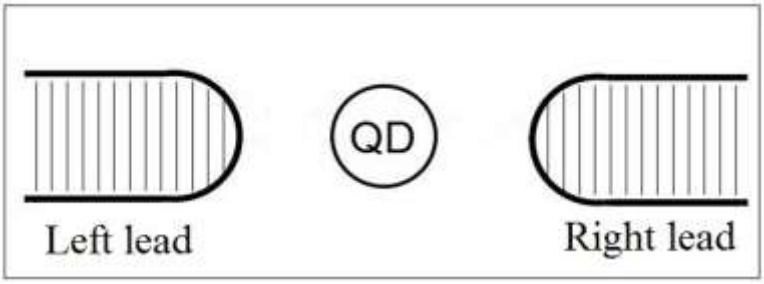

Fig.1 describesthe system under consideration

The energy diagram for the system described above in the absence of the electromagnetic fieldsand in the presence of bias voltage is shown in fig.(2) .

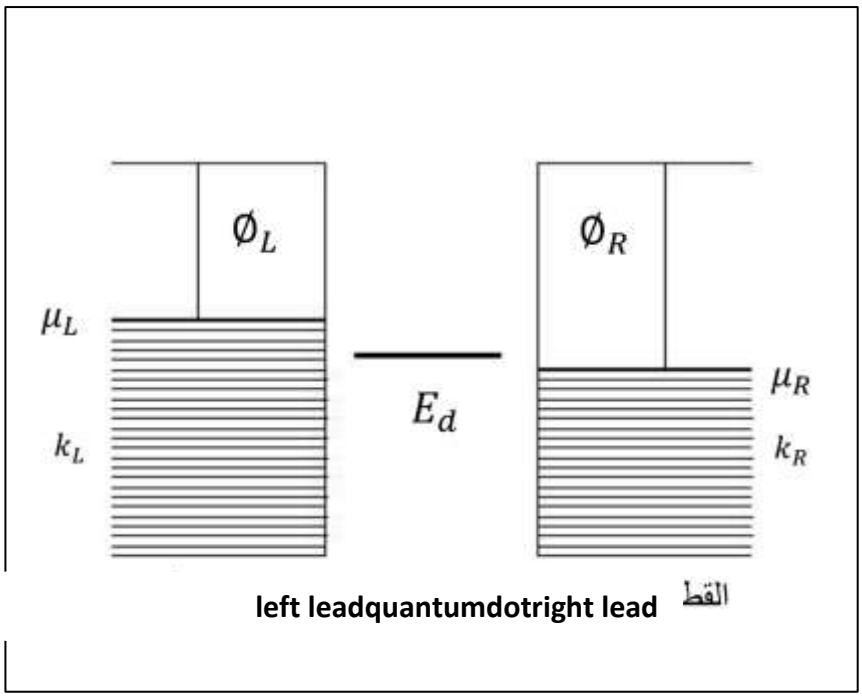

Fig.2 shows the energy diagram of the system under consideration in the absence of the electromagnetic fieldsand in the presence of bias voltage.

The Hamiltonion of the system can be written as[T. Kwapi´nskiet al.,2003] :

$$H(t) = H_1 + V(t) \quad (1)$$

$$H_1 = \sum_{\boldsymbol{k}} E_{\boldsymbol{k}}(t)\, C_{\boldsymbol{k}}^{\dagger} C_{\boldsymbol{k}} + E_d(t) C_d^{\dagger} C_d \quad (2)$$

$$V(t) = \sum_{\boldsymbol{k}} \left(V_{\boldsymbol{k}}(t)\, C_{\boldsymbol{k}}^{\dagger} C_d + V_{\boldsymbol{k}}^{*}(t)\, C_d^{\dagger} C_{\boldsymbol{k}} \right) \quad (3)$$

The operators $C_{k_L}, C_{k_R}\ and\ C_d\left(C_{k_L}^{+}, C_{k_R}^{+}\ and\ C_d^{+}\right)$ are the annihilation (creation) operators of the electron in the leads and in the QD, respectively. The coupling interactions between QD and lead states are denoted by $V_{\boldsymbol{k}_R d}$(t) and $V_{\boldsymbol{k}_L d}$(t) .$E_d(t)$ is the time dependent energy level of the quantum dot .$E_{\boldsymbol{k}_L}(t)$and $E_{\boldsymbol{k}_R}(t)$ refer to time dependent energy levels of left and right leads respectively .The corresponding electronic wave functions are$|k_L\rangle, |k_R\rangle$, and $|d\rangle$respectively.

We will describe the dynamical evolution of the charge localized on the QD and the current flowing in the system in terms of the time evolution operator $U(t,t_o)$in the (interaction representation) which satisfies the following equation[M. Tsukada *et al.*,1991]

$$i\ \frac{\partial U(t,t_o)}{\partial t}\ = \tilde{V}(t)U(t,t_o)(4)$$

Where

$$\tilde{V}(t) = e^{(iH_1\ (t-t_o))}\ V(t)\ e^{(-iH_1\ (t-t_o))} \quad (5)$$

By substituting eq.(3) in Eq.(5) , we get ,

$$\tilde{V}(t) = \sum_{\boldsymbol{k}_L}\left(\tilde{V}_{\boldsymbol{k}_L d}\ (t)\ C_{\boldsymbol{k}_L}^{+} + C_d + h.c.\right) + \sum_{\boldsymbol{k}_R}\left(\tilde{V}_{\boldsymbol{k}_R d}\ (t)\ C_{\boldsymbol{k}_R}^{+} + C_d + h.c.\right) \quad (6)$$

It is well known that in the adiabatic approximation ,the time dependent system energy levels are described by[T. Kwapi´nski*et al.*,2003]

E_{k_i}(t)= E_{k_i}(t) + $\Delta_i$cos(ωt)

E_d(t)= E_d(t) + $\Delta_d$cos(ωt) (7)

This means that the energy levels of the leads and the quantum dot are driven by the electromagnetic fields with frequency (ω) and amplitudes Δ_i ($i = R, L$) and Δ_d respectively

In general, the appropriate matrix elements of the evolution operators are given by ,

$U_{ij}(t,t_o) = \langle i|U(t,t_o)|j\rangle$ (8)

Since each $|i\rangle$ or $|j\rangle$ represent the quantum states of the system .The QD charge is given as follows [T.B. Grimley et al,.1983].

$$n_d(t) = n_d\ (t_o)\,|U_{dd}|^2 + \sum_{\boldsymbol{k}_L}\left(n_{K_L}\ (t_o)\,|U_{d\boldsymbol{k}_L}|^2\right) + \sum_{\boldsymbol{k}_R}\left(n_{\boldsymbol{k}_R}\ (t_o)\,|U_{d\boldsymbol{k}_R}|^2\right)$$

Where $n_d(t)$ is the occupation number of the quantum dot at time t .$U_{dd}(t,t_o)$,$U_{d\boldsymbol{k}_R}(t,t_o)$and $U_{d\boldsymbol{k}_L}(t,t_o)$ are the matrix elements of the time evolution operator which must be calculated within the basis function $|k_R\rangle, |k_L\rangle$ and $|d\rangle$. $n_d(t_o)$, $n_{\boldsymbol{k}_L}(t_o)$ and $n_{\boldsymbol{k}_R}(t_o)$ represent the initial filling on the quantum dot energy level , the right lead and the left lead respectivety .

While the current flowing from the left lead I_L(t) can be calculated from the time derivative of the total number of the electrons in the left lead n_L(t) ,which is given by [Jauho *et al.*,1994]

$$n_L(t)$$
$$= \sum\_(\boldsymbol{k}\_L)\blacksquare\ \langle\!\langle n\_d\ (t\_o\ )|U\_(\boldsymbol{k}\_L\ d)\dashv\ \vdash(t,t\_o\ )\dashv|\hat{}2\ \rangle\!\rangle$$
$$+\ \sum\_(\boldsymbol{k}\_L,\boldsymbol{k}\_L\hat{}\prime)\blacksquare\ \langle\!\langle n\_(\boldsymbol{k}\_L\hat{}\prime)\ (t\_o\ )|U\_(\boldsymbol{k}\_L,$$
$$\boldsymbol{k}\_L\hat{}\prime)\dashv\ \vdash(t,t\_o\ )\dashv|\hat{}2\ \rangle\!\rangle$$
$$+\sum\_(\boldsymbol{k}\_L,\boldsymbol{k}\_R)\blacksquare\ \langle\!\langle n\_(\boldsymbol{k}\_R\ )\ (t\_o\ )|U\_(\boldsymbol{k}\_L\ \boldsymbol{k}\_R\ )\dashv\ \vdash(t,t\_o\ )\dashv|\hat{}(2\quad)$$

In order to calculate $n_d(t)$, $n_L(t)$ and I_L(t) , the required set of equationsof motion for $U_{dd}(t,t_o)$,$U_{d\boldsymbol{k}_R}(t,t_o)$,$U_{d\boldsymbol{k}_L}(t,t_o)$, $U_{\boldsymbol{k}_L d}(t,t_o)$, $U_{\boldsymbol{k}_L,\boldsymbol{k}'_L}(t,t_o)andU_{\boldsymbol{k}_L\boldsymbol{k}_R}(t,t_o)$ as well as $U_{\boldsymbol{k}_R d}(t,t_o)$, $U_{\boldsymbol{k}_R,\boldsymbol{k}'_R}(t,t_o)$ and $U_{\boldsymbol{k}_R\boldsymbol{k}_L}(t,t_o)$ are all derived , keeping in mind that $U_{ij}(t,t_o)$ is not the complex conjugate of $U_{ji}(t,t_o)$ .If we get use eq.(4) , the time dependent equation for the matrix element simply will be ,

$$i\ (\partial U\_dd\ (t,t\_o\ ))/\partial t$$
$$=\ \langle d\left|\breve{V}(t)U(t,t\_o\ )\right|d\rangle \qquad (11)$$

Then , by using the following Indentity operator ,

$$\vdash I = |\ d\rangle\langle d\dashv\ |\ +\sum\_(\boldsymbol{k}\_L\hat{}\prime)\blacksquare\ |\ \vdash\boldsymbol{k}\_L\hat{}\prime\ \rangle\langle\boldsymbol{k}\_L\hat{}\prime\dashv\ |\ +\ \sum\_(\boldsymbol{k}\_R\hat{}\prime)\blacksquare\ |\ \vdash\boldsymbol{k}\_R\hat{}\prime\ \rangle\langle\boldsymbol{k}\_R\hat{}\prime\dashv$$
$$|\qquad\qquad (12)$$

We get ,

$$i\ (\partial U\_dd\ (t,t\_o\ ))/\partial t\ =\ \langle d\left|\breve{V}(t)\right|d\rangle\ U\_dd\ (t,t\_o\ )$$

$$+\sum\_(\boldsymbol{k}\_L)\blacksquare\ \langle\!\langle d\left|\breve{V}(t)\right|\boldsymbol{k}\_L\ \rangle\ U\_(\boldsymbol{k}\_L\ d)\ (t,t\_o\ )\ \rangle\!\rangle$$
$$+\ \sum\_(\boldsymbol{k}\_R)\blacksquare\ \langle\!\langle d\left|\breve{V}(t)\right|\boldsymbol{k}\_R\ \rangle\ \ \langle\!\langle U\rangle\!\rangle\ \_(\boldsymbol{k}\_R\ d)\ (t,t\_o\ ) \qquad (13)\rangle\!\rangle$$

By subsituting eq. (6) in eq.(13) , then we get use of the creation (annihilation) operators properties to summarize all the mathematical and logic steps we needed to get eq.(14) in table (1) . The line (———) in table (1) means that the mentioned process is not valid .

$$i(\partial U\_dd\ (t,t\_o\ ))/\partial t$$
$$=\ \sum\_(\boldsymbol{k}\_L)\blacksquare\ \langle\!\langle\breve{V}\_(d\boldsymbol{k}\_L\ )\ (t)\ \ \langle\!\langle U\rangle\!\rangle\ \_(\boldsymbol{k}\_L\ d)\ (t,t\_o\ )\ \rangle\!\rangle$$
$$+\sum\_(\boldsymbol{k}\_R)\blacksquare\ \langle\!\langle\breve{V}\_(d\boldsymbol{k}\_R\ )\ (t)\ U\_(\boldsymbol{k}\_R\ \ d)\ (t,t\_o\ ) \qquad (14\rangle\!\rangle)$$

Similarly ,we accomplish table (2)to obtain ,

$$i\ (\partial U\_(\boldsymbol{k}\_L\ d)\ (t,t\_o\ ))/\partial t$$
$$=\ \breve{V}\_(\boldsymbol{k}\_L\ d)\ (t)\ U\_dd\ (t,t\_o\ ) \qquad (15)$$

and table (3) , we get ,

$$i(\partial U\_(\boldsymbol{k}\_R\ d)\ (t,t\_o\ ))/\partial t$$
$$=\ \ \breve{V}\_(\boldsymbol{k}\_R\ d)\ (t)\ U\_dd\ (t,t\_o\ ) \qquad (16)$$

Following the same procedure , we obtain ,

$$i\,(\partial U\_(d\boldsymbol{k}\_L\hat{}')\,(t,t\_o\,))/\partial t$$
$$=\sum\_(\boldsymbol{k}\_L)\blacksquare\ [\![\tilde{V}\_(d\boldsymbol{k}\_L\,)\,(t)\ \ [\![U]\!]\ \_(\boldsymbol{k}\_L\,\boldsymbol{k}\_L\hat{}')\,(t,t\_o\,)\ ]\!]$$
$$+\sum\_(\boldsymbol{k}\_R)\blacksquare\ [\![\tilde{V}\_(d\boldsymbol{k}\_R\,)\,(t)\,U\_(\boldsymbol{k}\_R\,\boldsymbol{k}\_L\hat{}')\,(t,t\_o\,)\ ]\!] \qquad (17)$$

$$i(\partial U\_(\boldsymbol{k}\_L\,\boldsymbol{k}\_L\hat{}')\,(t,t\_o\,))/\partial t$$
$$=\tilde{V}\_(\boldsymbol{k}\_L\,d)\,(t)\,U\_(d\boldsymbol{k}\_L\hat{}')\,(t,t\_o\,) \qquad (18)$$

$$i\,(\partial U\_(\boldsymbol{k}\_R\,\boldsymbol{k}\_L\hat{}')\,(t,t\_o\,))/\partial t$$
$$=\tilde{V}\_(\boldsymbol{k}\_R\,d)\,(t)\,U\_(d\boldsymbol{k}\_L\hat{}')\,(t,t\_o\,) \qquad (19)$$

$$i\,(\partial U\_(d\boldsymbol{k}\_R\hat{}')\,(t,t\_o\,))/\partial t$$
$$=\sum\_(\boldsymbol{k}\_L)\blacksquare\ [\![\tilde{V}\_(d\boldsymbol{k}\_L\,)\,(t)\ \ [\![U]\!]\ \_(\boldsymbol{k}\_L\,\boldsymbol{k}\_R\hat{}')\,(t,t\_o\,)\ ]\!]$$
$$+\sum\_(\boldsymbol{k}\_R)\blacksquare\ [\![\tilde{V}\_(d\boldsymbol{k}\_R\,)\,(t)\,U\_(\boldsymbol{k}\_R\,\boldsymbol{k}\_R\hat{}')\,(t,t\_o\,)\ ]\!] \qquad (20)$$

$$i\,(\partial U\_(\boldsymbol{k}\_L\,\boldsymbol{k}\_R\,)\,(t,t\_o\,))/\partial t$$
$$=\tilde{V}\_(\boldsymbol{k}\_L\,d)\,(t)\,U\_(d\boldsymbol{k}\_R\,)\,(t,t\_o\,) \qquad (21)$$

$$i\,(\partial U\_(\boldsymbol{k}\_R\,\boldsymbol{k}\_R\hat{}')\,(t,t\_o\,))/\partial t$$
$$=\tilde{V}\_(\boldsymbol{k}\_R\,d)\,(t)\,U\_(d\boldsymbol{k}\_R\hat{}')\,(t,t\_o\,) \qquad (22)$$

To simplify the set of equations (14-22) , we use energy phase separation procedure ,

$$\tilde{V}_{i\boldsymbol{k}_\alpha}(t)=v_{\boldsymbol{k}_\alpha}V_{i\alpha}(t)$$

$$[\![U]\!]\_(\ [\![i\boldsymbol{k}]\!]\ \_\alpha\,)\,(t,t\_o\,)=\ [\![v\_(\boldsymbol{k}\_\alpha)\hat{}*\,]\!]\ \_\,U\_i\alpha\,(t,t\_o\,) \qquad (23)$$

$$[\![U]\!]\ \_(\boldsymbol{k}\_i\,\boldsymbol{k}\_j\,)\,(t,t\_o\,)=\ [\![v\_(\boldsymbol{k}\_i)\hat{}*\ v\_(\boldsymbol{k}\_j)\hat{}*\,]\!]\ \_\,U\_ij\,(t,t\_o\,)$$

the Dirac delta function properties and the leads density of states ,

$$\rho\_\alpha\,(E\_\alpha\,)=\sum\_(\boldsymbol{k}\_\alpha)\blacksquare|v\_(\boldsymbol{k}\_\alpha\,)\,|\hat{}2\ \delta(E\_\alpha - E\_(\boldsymbol{k}\_\alpha\,)\,) \qquad (24)$$

We get ,the following set of equations which can simply numerically solved by using six-order Runge-Kutta method in the wide band limit ,

$$i(\partial U\_dd\,(t,t\_o\,))/\partial t=\bar{\rho}\_L\int\blacksquare\ [\![dE\_L\,]\!]\ V\_dL\,(t)\,U\_Ld\,(E\_L,t,t\_o\,)$$
$$+\bar{\rho}\_R\int\blacksquare\ [\![dE\_R\,V\_dR\,(t)\,U\_Rd\,(E\_R,t,t\_o\,)\ ]\!] \qquad (25)$$

$$i\,\partial/\partial t\,U\_Ld\,(E\_L,t,t\_o\,)$$
$$=V\_Ld\,(t)\,U\_dd\,(t,t\_o\,) \qquad (26)$$

$$i\,\partial/\partial t\,U\_Rd\,(E\_R,t,t\_o\,)$$
$$=V\_Rd\,(t)\,U\_dd\,(t,t\_o\,) \qquad (27)$$

$$i\,\partial/\partial t\,U\_(dL\hat{}')\,(E\_L\hat{}',t,t\_o\,)$$
$$=\bar{\rho}\_L\int\blacksquare\ [\![dE\_L\,]\!]\ V\_dL\,(t)\,U\_(LL\hat{}')\,(E\_L,E\_L\hat{}',t,t\_o\,)$$
$$+\bar{\rho}\_R\int\blacksquare\ [\![dE\_R\,V\_dR\,(t)\,U\_(RL\hat{}')\,(E\_R,E\_L\hat{}',t,t\_o\,)$$

$$i\,\partial/\partial t\,U\_(LL\hat{}')\,(E\_L,E\_L\hat{}',t,t\_o\,)$$
$$=V\_Ld\,(t)\,U\_(dL\hat{}')\,(E\_L\hat{}',t,t\_o\,) \qquad (29)$$

$$i\,\partial/\partial t\; U\_(RL\hat{}')\,(E\_R, E\_L\hat{}', t, t\_o\,) = V\_Rd\,(t)\; U\_(dL\hat{}')\,(E\_L\hat{}', t, t\_o\,) \quad (30)$$

$$i\,\partial/\partial t\; U\_(dR\hat{}')\,(E\_R\hat{}', t, t\_o\,) = \rho\bar{}\_L \int \text{▒}\; \llbracket dE\_L \rrbracket\; V\_dL\,(t)\; U\_(LR\hat{}')\,(E\_L, E\_R\hat{}', t, t\_o\,) + \rho\bar{}\_R \int \text{▒}\; \llbracket dE\_R\, V\_dR\,(t)\; U\_(RR\hat{}')\,(E\_R, E\_R\hat{}', t, t\_o\,) \rrbracket$$

$$i\,\partial/\partial t\; U\_(RR\hat{}')\,(E\_R, E\_R\hat{}', t, t\_o\,) = V\_Rd\,(t)\; U\_(dR\hat{}')\,(E\_R\hat{}', t, t\_o\,) \quad (32)$$

$$i\,\partial/\partial t\; U\_(LR\hat{}')\,(E\_L, E\_R\hat{}', t, t\_o\,) = V\_Ld\,(t)\; U\_(dR\hat{}')\,(E\_R\hat{}', t, t\_o\,) \quad (33)$$

The interactions between thequantum dot andleads are switched on at time t_o, i.e. the hybridization matrix elements are equal to zero for $t \le t_o$.

Tabl1 (1) : The matrix elements of $\langle d|\tilde{V}(t)|j\rangle$ with j= d , k'_L, k'_R .

ket / bra	$\mid d\rangle$	$\sum_{k'_L} \mid k'_L\rangle$	$\sum_{k'_R} \mid k'_R\rangle$
$\langle d \mid \sum_{k_L} \tilde{V}_{k_L d}(t) C^+_{k_L} C_d$	$\tilde{V}_{k_L d}(t)\langle d\mid k_L\rangle = 0$	——	——
$\langle d \mid \sum_{k_L} \tilde{V}_{d k_L}(t) C^+_d C_{k_L}$	——	$\sum_{k_L} \tilde{V}_{d k_L}(t)\langle d\mid d\rangle$	——
$\langle d \mid \sum_{k_R} \tilde{V}_{k_R d}(t) C^+_{k_R} C_d$	$\tilde{V}_{k_R d}(t)\langle d\mid k_R\rangle = 0$	——	——
$\langle d \mid \sum_{k_R} \tilde{V}_{d k_R}(t) C^+_d C_{k_R}$	——	——	$\sum_{k_R} \tilde{V}_{d k_R}(t)\langle d\mid d\rangle$

Tabl1 (2) : The matrix elements of $\langle k''_L|\tilde{V}(t)|j\rangle$ with j= d , k'_L,k'_R

ket / bra	$\mid d\rangle$	$\sum_{k'_L} \mid k'_L\rangle$	$\sum_{k'_R} \mid k'_R\rangle$
$\langle k''_L \mid \sum_{k_L} \tilde{V}_{k_L d}(t) C^+_{k_L} C_d$	$\tilde{V}_{k_L d}(t)\langle k''_L\mid k_L\rangle$	——	——
$\langle k''_L \mid \sum_{k_L} \tilde{V}_{d k_L}(t) C^+_d C_{k_L}$	——	$\tilde{V}_{d k_L}(t)\langle k''_L\mid d\rangle = 0$	——
$\langle k''_L \mid \sum_{k_R} \tilde{V}_{k_R d}(t) C^+_{k_R} C_d$	$\tilde{V}_{k_R d}(t)\langle k''_L\mid k_R\rangle = 0$	——	——
$\langle k''_L \mid \sum_{k_R} \tilde{V}_{d k_R}(t) C^+_d C_{k_R}$	——	——	$\tilde{V}_{d k_R}(t)\langle k''_L\mid d\rangle = 0$

Tabl1 (3) : The matrix elements of $\langle k_R''|\tilde{V}(t)|j\rangle$ with j= d , k_L', k_R' .

ket / bra	$\|\, d\rangle$	$\sum_{k_L'} \|\, k_L'\rangle$	$\sum_{k_R'} \|\, k_R'\rangle$
$\langle k_R'' \| \sum_{k_L} \tilde{V}_{k_L d}(t) C_{k_L}^{+} C_d$	$\tilde{V}_{k_L d}(t)\langle k_R''\|k_L\rangle = 0$	——	——
$\langle k_R'' \| \sum_{k_L} \tilde{V}_{d k_L}(t) C_d^{+} C_{k_L}$	——	$\tilde{V}_{d k_L}(t)\langle k_R''\|d\rangle = 0$	——
$\langle k_R'' \| \sum_{k_R} \tilde{V}_{k_R d}(t) C_{k_R}^{+} C_d$	$\tilde{V}_{k_R d}(t)\langle k_R''\|k_R\rangle$	——	——
$\langle k_R'' \| \sum_{k_R} \tilde{V}_{d k_R}(t) C_d^{+} C_{k_R}$	——	——	$\tilde{V}_{d k_R}(t)\langle k_R''\|d\rangle = 0$

3.Results and Discussion

The set of integro-differential equations (25 - 33) are solve numerically by using Rung-kutta method with time increment $\Delta t = 10^{-3}$a.u. . All the energy integration are performed numerically by using Simpson method with energy increment $\Delta E = 0.1\ eV$.

The bias voltage V_b between the left and right lead is given by $\mu_L - \mu_R = eV_b$, μ_R is fixed at the energy reference(E=0) ,while μ_L is fixed at 4 eV .While T is equal to 0 K .In the wide band limit the lead density of states $\bar{\rho}_\beta = \frac{1}{4\beta}$, 4β is the band width where β is chosen to be 5 eV . At t_o(=0) , the occupation number of the quantum dot $n_d(t_o) = 0$ with $E_d = 1\ eV$. The external field parameter are $\hbar\omega$=1 eV , Δ_L= 4 eV , Δ_d= 2 eV and Δ_R= 0 eV .

The coupling interaction $V_{ij}(t)$ is calculated by using the following relation [R. Taranko *et al.*,2004] :-

$$\tilde{V}_{ij}(t) = V_{ij}(t)\ exp\left(i(\varepsilon_i - \varepsilon_j)(t - t_o)\right) \times exp\left(i\frac{\Delta_i - \Delta_j}{\omega}(sin\omega t - sin\omega t_o)\right) \qquad (34)$$

In order to check the program accuracy , we performed our calculations (for the current I_L (t) for two values of increments $\Delta t = 10^{-3}$ and $\Delta t = 10^{-4}$a.u. as shown in fig.(3) ,which shows good agreement.

The current I_L flowing from the left lead is given by the following relation [R. Taranko *et al.*,2004],

$$I\_L\ (t) = 2Re[n\_d\ (t\_0\ )\sum\_(k\_L)\text{▒}[\![U\_(k\_L\ d)\hat{}\ *\ (t, t\_o\ )(\partial/\partial t\ U\_(k\_L\ d)\ (t, t\_o\ ))\ ]\!] + \sum\_(k\_L\ q\_L)\text{▒}[\![n\_\boldsymbol{q}L\ \ [\![(t\_0\ )\ U]\!]\ \_(k\_L\ qL)\hat{}\ * (t, t\_o\ )(\partial/\partial t\ U\_(k\_L\ qL)\ (t, t\_o\ ))\ ]\!] + \sum\_(k\_L\ k\_R)\text{▒}[\![n\_kR\ \ [\![(t\_0\ )\ U]\!]\ \_(k\_L\ k\_R)\hat{}\ * (t, t\_o\ )(\partial/\partial t\ U\_(k\_L\ k\_R\ )\ (t, t\_o\ ))\ ]\!]] \qquad (35)$$

Accordingly ,we write the tunnelling current as follow,

$$I\_L\ (t)$$
$$= 2Re[n\_d\ (t\_0\ )\ \bar{\rho}\_L \int \_(k\_L)\blacksquare\ \llbracket U\_(k\_L\ d)\hat{}\ *\ (\partial/\partial t\ U\_(k\_L\ d)\ )dk\_L$$
$$+\ \rrbracket\ \bar{\rho}\_L \int \_(k\_L)\blacksquare\ \llbracket dk\_L\hat{}'\ \rrbracket\ [\bar{\rho}\_(L\hat{}'\ ) \int \_(k\_L\hat{}')\blacksquare\ \llbracket\ \llbracket f(k\_L\hat{}', T)U\rrbracket\ \_(k\_L\ k\_L\hat{}')\hat{}$$
$$*\ (\partial/\partial t\ U\_(k\_L\ k\_L\hat{}'\ )\ )dk\_L\ \rrbracket\ ]$$
$$+\ \bar{\rho}\_L \int \_(k\_L)\blacksquare\ \llbracket dk\_L\ \rrbracket\ [\bar{\rho}\_R \int \_(k\_R)\blacksquare\ \llbracket\ \llbracket f(k\_R, T)U\rrbracket\ \_(k\_L\ k\_R)\hat{}$$
$$*\ (\partial/\partial t\ U\_(k\_L\ k\_R\ )\ )dk\_R\ \rrbracket\ ]] \qquad (36)$$

The results of eq.(36) are compared with numerical one that we calculate by using finite differences . Both results are coincident (see fig.(4))

We calculate the quantum dot charge $n_d(t)$, the total number of electrons in the left lead $n_L(t)$ and the tunnelling current $I_L(t)$ as a function of time by using the over mentioned parameters . These results are shown in figs.(5-9) , from which we conclude the following :-

1 – The Charge on the left lead is determined by the initial charge on the quantum dot (as shown in fig.(5)) .In general, their relations with time are opposite ,which physically logic . While the nearly periodic behaviour of the tunnelling current is severd after t=20 a.u.

2 – In fig.(6) the charge on the left lead is greater for the case of $E_d = 4\ eV$, which is in resonance with the position of μ_L, in spite of the position of $E_d(= 1$ eV) is localized below the energy position of the left lead chemical potential . The current shows periodic oscillations with certain shift for different values of $n_d(t_o)$. In general the tunnelling current in large for $n_d(t_o)$=1 ,which is logic.

3 – The electromagnetic fields characteristics (that apply to the subsystems) are also investigated as shown in figs.(7) and (8) . The total number of the electrons on the left lead increases as Δ_L and ω increase .The increasing of the frequency may increase the tunnelling current but not at all time . For the case of $\Delta_d = \Delta_L$, we need to calculate the average value of the tunnelling current to write final conclusion

4 – The effect of the left lead chemical potential position is also investigated (see fig.(4)). It is obvious that the tunnelling current increases as the energy spacing between the left lead chemical potential position and the quantum dot energy level position increases .

Finally, in our future work we will calculate the time average tunnelling current $\langle I_L(t)\rangle$ as a function of all the over mentioned parameters , which all participate in determining the relation of $\langle I_L(t)\rangle$ with one of them as it is concluded .

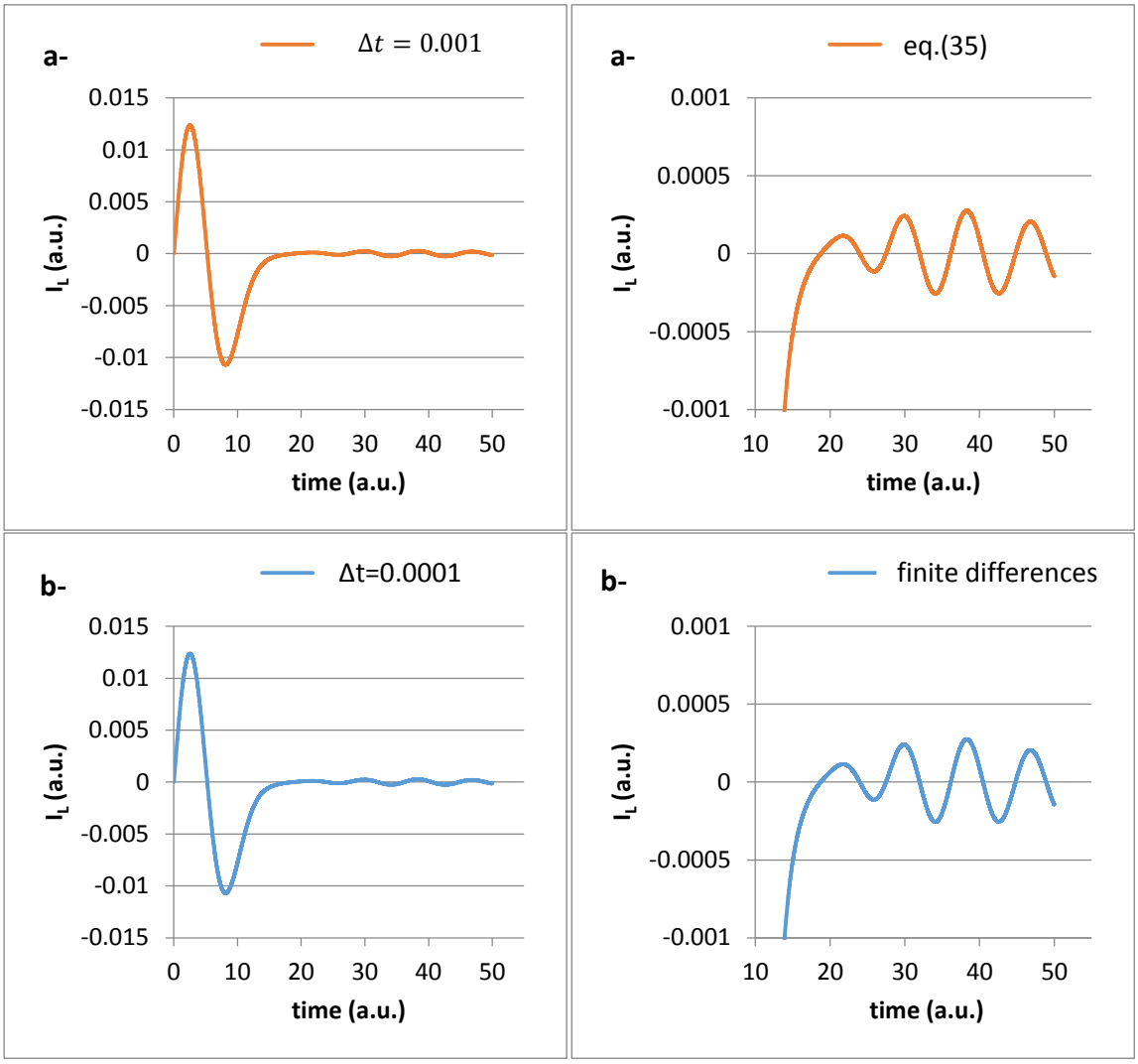

Fig.(3) : The time dependent current flowing from the left lead :

a – values of increments $\Delta t = 10^{-3}$

b – values of increments $\Delta t = 10^{-4}$

$\beta = 5\ eV$, $w = 1\ eV$, $\Delta_L = 4\ eV$, $\Delta_d = 2\ eV$

$\mu_L = 2\ eV$, $\mu_R = 0$, $\Delta_R = 0$, $E_d = 1eV$, $n_d = 0$

Fig.(4) : The time dependent current flowing from the left lead :

a – calculated by eq.(35)

b – calculated by using finite difference

$\beta = 5\ eV$, $w = 1\ eV$, $\Delta_L = 4\ eV$, $\Delta_d = 2\ eV$

$\mu_L = 2\ eV$, $\mu_R = 0$, $\Delta_R = 0$, $E_d = 1\ eV$, $n_d = 0$

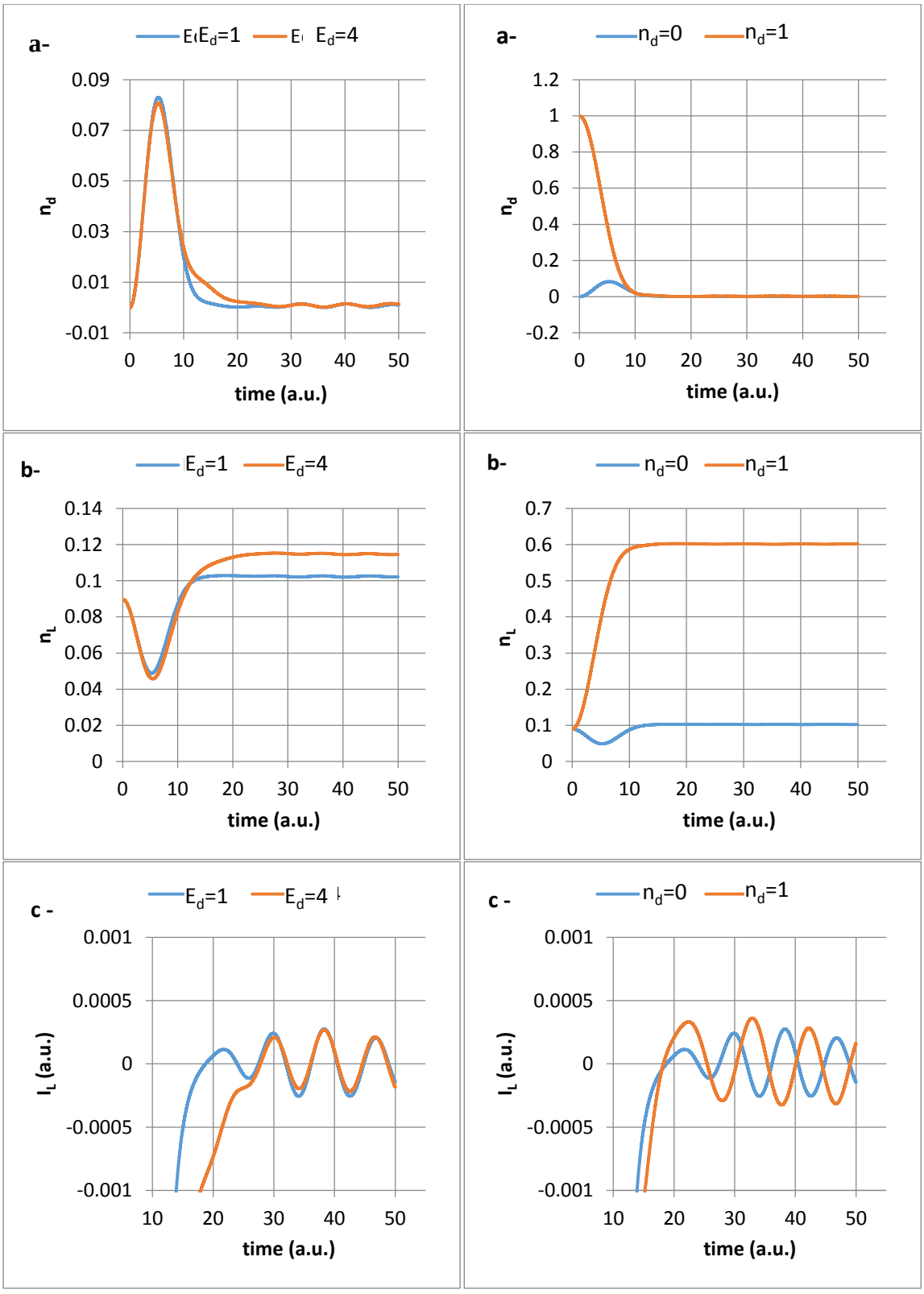

Fig.(5) : The time-dependent of the charge on quantum dot (a),the charge on left lead (b) and the current flowing from the left lead (c) with

$\beta = 5\ eV$, $w = 1\ eV$, $\Delta_L = 4\ eV$, $\Delta_d = 2\ eV$

$\mu_L = 2\ eV$, $\mu_R = 0$, $n_d = 0$, $\Delta_R = 0$

Fig.(6) : The time-dependent of the charge on quantum dot (a),the charge on left lead (b) and the current flowing from the left lead(c) with

$\beta = 5\ eV$, $w = 1\ eV$, $\Delta_L = 4\ eV$, $\Delta_d = 2\ eV$

$\mu_L = 2\ eV$, $\mu_R = 0$, $E_d = 1\ eV$, $\Delta_R = 0$

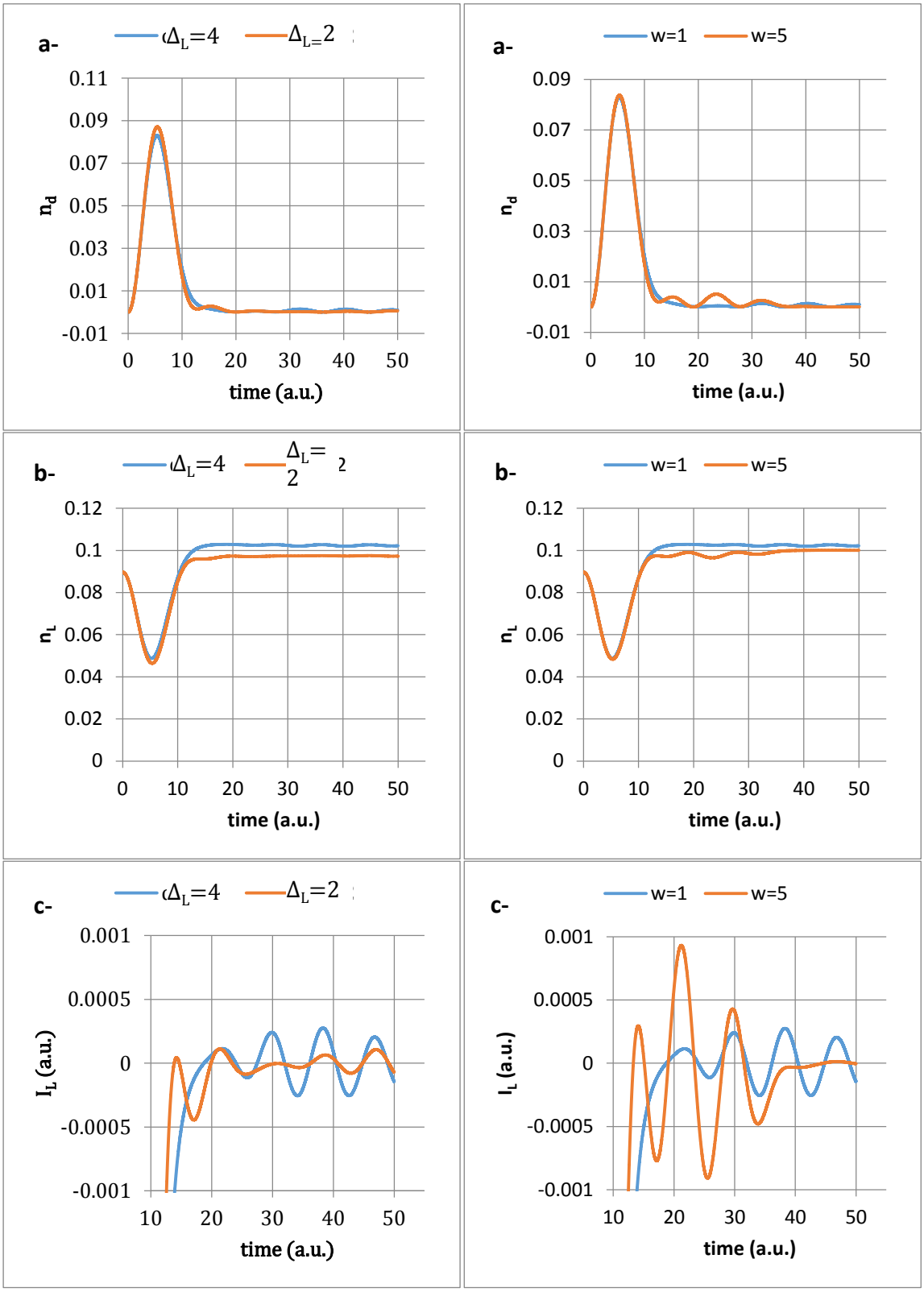

Fig.(7) : The time-dependent of the charge on quantum dot (a),the charge on left lead (b) and the current flowing from the left lead(c) with

$\beta = 5\ eV$, $w = 1\ eV$, $n_d = 0$, $\Delta_d = 1eV$

$\mu_L = 2\ eV$, $\mu_R = 0$, $E_d = 1\ eV$, $\Delta_R = 0$

Fig.(8) : The time-dependent of the charge on quantum dot (a),the charge on left lead (b) and the current flowing from the left lead(c) with

$\beta = 5\ eV$, $n_d = 0$, $\Delta_L = 4\ eV$, $\Delta_d = 2\ eV$

$\mu_L = 2\ eV$, $\mu_R = 0$, $E_d = 1\ eV$, $\Delta_R = 0$

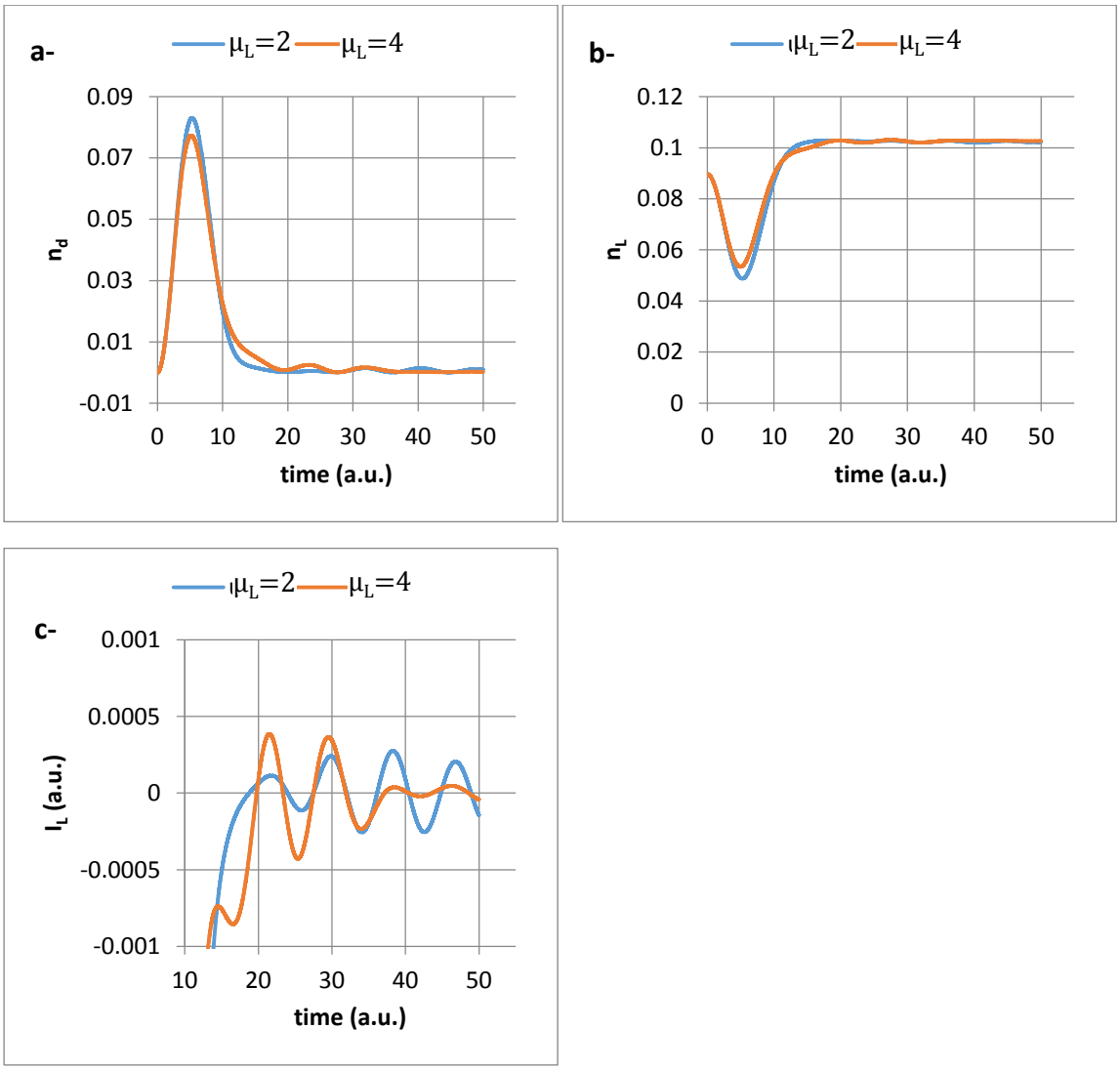

Fig.(9) : The time-dependent of the charge on quantum dot (a),the charge on left lead (b) and the current flowing from the left lead(c) with

$\beta = 5\ eV$, $w = 1\ eV$, $n_d = 0$, $\Delta_d = 2\ eV$

$\Delta_L = 4eV$, $\mu_R = 0$, $E_d = 1\ eV$, $\Delta_R = 0$

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نقل الكترون المعتمد على الزمن خلال نقطة كمية بغياب القناة الغير رنينية

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الملخص :

في هذا العمل ، درسنا خصائص نقل الإلكترون في نقطة كمية بوجود المجالات الكهرومغناطيسية و بغياب القناة غير الرنينية ، بأستخدام تقنية مؤثر زمن–نمو . تم أخذ بنظر الإعتبار تأثير كل من التردد والسعة للمجال الكهرومغناطيسي على الأقطاب والنقطة الكمية. كذلك تم اشتقاق معادلات الحركة للنظام وحلها عدديا باستخدام تقريب الحزمة العريضة . وتم حساب شحنه النقطة الكمية وعدد الاشغال الكلي للإلكترونات على القطب الأيسر والتيار المنبعث من القطب الأيسر ، كذلك تم حساب ذلك لمدى واسع من البارامترات .