High Performance of Nonlinear Active Rectifier Voltage and Power

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High Performance of Nonlinear Active Rectifier Voltage and Power Factor Control Using Feedback Linearization

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Abstract – Nonlinear property of Active rectifier is caused by the use of the semiconductor switches, resulting in high harmonic distortion and high ripple output voltage on the DC side. This research develops a nonlinear controller to improve performance of the dc output voltage and line current based on feedback linearization. . This controller mathematically transform nonlinear system dynamics into fully linear ones, so that linear control techniques can be applied. It is designed with selecting energy function on DC side and quadrature-axis current on AC side as output variables, in order to avoid the internal dynamics, so that the system becomes stable and robust. The system applies switch function of time as the input of control strategy, instead of current and voltage in d-q frame. The proposal is validated through different tests. These tests include difference performance with conventional controller (PI optimized). The simulation results in that the output voltage performing without any overshoot, while the ripple and settling time is 0.006 sec, which is better result compared to PI optimized.

***Keywords**: Active Rectifier, Feedback Linearization, PI Optimized.*

Nomenclature

V_{dc}	DC voltage (V)
S	Switch function
i	Line current (A)
e	Source line voltage (V)
R	Line resistance (Ω)
L	Line inductance (H)
i_L	Load current (A)
C_{dc}	DC capasitance (F)
w_c	DC energy function (Joule)
e_w	DC tracking error
e_q	quadratic current tracking error
k_{11}, k_{12}, k_{13}, k_{21}, k_{22}	gain

Subscript Superscripts and Operators

*	Reference value
d, q	Direct, quadrature axis component
a, b, c	phasa a, phasa b, phasa c

I. Introduction

Active Rectifier is widely used in many power electronics fields. It has feature such as providing constant DC bus voltage, low harmonic distortion of utility currents, high power factor and bidirectional power flow. Due to these features, the active rectifier is a good choice for application in industrial drives [1],[2]. The active rectifier is nonlinear system. In general, this nonlinear impacts are not expected (for example , ripple on DC voltage, harmonics in the line current and the low value of power factor) so that is required proper controller that can compensate them. Many researches focus on the control principle of active rectifier of dealing nonlinearity property. For example, two of classical linear PID controllers to regulate the DC voltage and the harmonic of current line. PID controllers were considered as simple and robust techniques [3[-[5]. However, one of the drawbacks in using PID control techniques was that they were not sufficient to obtain the desired tracking control performance because of the nonlinearity of the active rectifier. Other researchers have applied the method known as fuzzy logic controller and Neural networks [6]-[8]. Fuzzy Logic is one of nonlinear controller but it is unstructure controller, vice versa active rectifier is structured system. Researchers also have developed several nonlinear controllers in order to control Active Rectifier. Controllers based on Jacobian linearisation around an equilibrium point have been introduced in [9]-[10], however, this strategy presents some drawbacks. Among others, operation range is restricted and a relatively big output capasitor is needed
for keeping a constant DC voltage in presence of a varying load, backstepping technique [11], [12]. Then, nonlinear approaches also have been proposed by other researchers, that is input output linearization based on feedback linearization [13]-[19]. This technique mathematically transform nonlinear system dynamics into fully or partly linear ones, so that linear control techniques can be applied. Then linear control laws can be used for guaranteeing stability in the whole operation range.In this technique depends on selected output variabels. In this paper [15] selects DC voltage and direct current as output

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variables, a nonlinear unstable internal dynamics appears. In [16] author have selected difference between the voltage source and the voltage active rectifier on AC side as input variabel, then variabels DC voltage and direct axis current as input. Some many authors have proposed converter energy as output in feedback controller design to accomplish a minimum-phase output and faster DC-voltage control [17]-[18].

This paper proposes a nonlinear multivariable control technique based on feedback linearization theory with selecting energy function on DC side and quadrature-axis current on AC side as output variables. One of the primary advantages of this nonlinear controller can avoid internal dynamics and zero dynamics. For this reason, the proposed technique avoids the drawback appearing in other proposals due to the coupling between the inner current loop and outer voltage loop.

The paper is organized as follows. In section II, the proposed control strategy is presented. The mathematical model expressed in a d-q synchronous reference frame of the Active Rectifier was derived in section III. Design of the feedback linearization control strategy that consist of non linear transformation and design of linear control have developed in section IV. The performance evaluation, simulation results and compared with conventional controller (PI optimized) are presented in section V. Finally, conclusion are drawn in section VI.

II. Proposed Control Strategy

The proposed system uses dynamic model of active rectifier in a synchronous d-q reference frame. The system applies switch function in d-q frame (s_d, s_q) as the input of control strategy, instead of current and voltage.

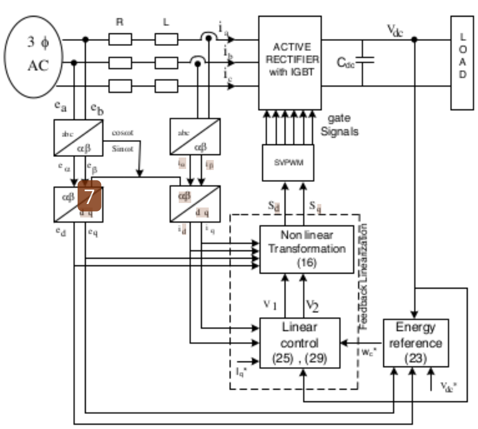


Fig. 1. Block Diagram of the Proposed Control Strategy

In Fig. 1, an energy reference block is used to produce the energy reference of the DC side (w_C^*) that is calculated by using equation (23). The DC voltage of the active rectifier (V_{dc}) can be controlled through this energy function. The linear control block shown is obtained from equations tracking control (25) and (29), so producing the new control inputs v_1 and v_2. The nonlinear control block in Fig.1 is used for transforming v_1, v_2 become s_d, s_q by using control law in equation (16).

III. Modelling of The System

A three-phase mathematical model for the active rectifier is derived in [20]-[21]. Fig. 2 represents the topology of the three phase active rectifier.

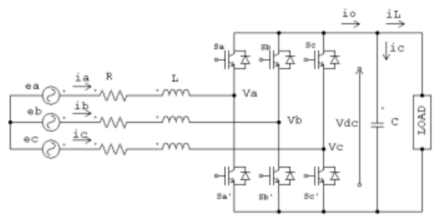


Fig. 2. The topology of the three-phase active rectifier system

the active rectifier can be modeled as

$$L\frac{di_a}{dt}+Ri_a=e_a-V_{dc}\left(S_a-\frac{1}{3}(S_a+S_b+S_c)\right)$$
$$L\frac{di_b}{dt}+Ri_b=e_b-V_{dc}\left(S_b-\frac{1}{3}(S_a+S_b+S_c)\right) \quad (1)$$
$$L\frac{di_c}{dt}+Ri_c=e_c-V_{dc}\left(S_c-\frac{1}{3}(S_a+S_b+S_c)\right)$$

$$C\frac{dV_{dc}}{dt}=\left(i_aS_a+i_bS_b+i_cS_c\right)-i_L \quad (2)$$

The model presented in (1) and (2) is transformed into a synchronous d-q reference frame, resulting in :

$$L\dot{i}_d=-Ri_d-L\omega i_q-s_dV_{dc}+e_d \quad (3)$$
$$L\dot{i}_q=-Ri_q+L\omega i_d-s_qV_{dc}+e_q \quad (4)$$
$$C_{dc}\dot{V}_{dc}=\frac{3}{2}\left(s_di_d+s_qi_q\right)-\frac{V_{dc}}{R_L} \quad (5)$$

Where ω is the angular frequency of the source voltage and R_L is resistive load that connected to the output terminal.

Equation (3) – (5) are then reconstructed considering a multi-input multi-output (MIMO) system as follows [22]:

$$\dot{x}=f(x)+g(x)u \quad (6)$$
$$y=h(x) \quad (7)$$

where
x is the state vector;
u is control input vector;
y is vector of system outputs;
f, and g are smooth vector fields;
h is smooth scalar

The vectors are defined as follows :

$$\dot{x}=\begin{bmatrix} \dot{i}_d \\ \dot{i}_q \\ \dot{V}_{dc} \end{bmatrix} \; ; \; f(x)=\begin{bmatrix} -\frac{R}{L}i_d - \omega i_q + \frac{e_d}{L} \\ -\frac{R}{L}i_q + \omega i_d + \frac{e_q}{L} \\ -\frac{V_{dc}}{R_L C_{dc}} \end{bmatrix}$$

$$g(x)=\begin{bmatrix} -\frac{V_{dc}}{L} & 0 \\ 0 & -\frac{V_{dc}}{L} \\ \frac{3i_d}{2C_{dc}} & \frac{3i_q}{2C_{dc}} \end{bmatrix} \; ; \; u=\begin{bmatrix} S_d \\ S_q \end{bmatrix} \qquad (8)$$

The active rectifier has two output variables. First ouput variable is energy function on DC side (w_c). Through this function, the DC voltage of active rectifier can be controlled. The second output variable is Quadrature-axis current (i_q). This ouput is used to control power factor and harmonic distortion. By choosing these outputs, the total of relative degree of is three that equals to order of the active rectifier, so that, the system can be avoided from internal dynamic, then complete feedback linearization is obtained and two linear decoupled loops are to be controlled.

The variables of system output are

$$y=\begin{bmatrix} w_C \\ i_q \end{bmatrix} \quad ; \quad h(x)=\begin{bmatrix} \frac{L}{2}\left(i_d^2+i_q^2\right)+\frac{C_d c}{3}V_{dc}^2 \\ i_q \end{bmatrix} \qquad (9)$$

Below is the description to find the energy function of equation (9). Energy is obtained from power balance equation relating the AC side power P_{ac} and the DC side power P_{dc}

$$P_{dc}=P_{ac}$$

$$V_{dc}i_o=\frac{3}{2}\left(s_d V_{dc} i_d + s_q V_{dc} i_q\right) \qquad (10)$$

Assuming the net power in the DC side is stored in the capasitor, then the output current i_o is replaced with capasitor current $C_{dc}\frac{dV_{dc}}{dt}$. The equation (10) can be rewritten is

$$C_{dc}\frac{dV_{dc}}{dt}=\frac{3}{2}\left(i_d S_d + i_q S_q\right) \qquad (11)$$

From the dynamic model of the active rectifier, the entire power is calculated from equation (3) and (4) multiplied with i_d and i_q respectively

$$Li_d\dot{i}_d = -Ri_d^2 - L\omega i_q i_d - s_d V_{dc} i_d + e_d i_d \qquad (12)$$

$$Li_q\dot{i}_q = -Ri_q^2 + L\omega i_d i_q - s_q V_{dc} i_q + e_q i_q \qquad (13)$$

By summing equation (11), (12) and (13), a new equation of power is found as follows :

$$\left\{ i_d L\frac{di_d}{dt} + i_q L\frac{di_q}{dt} + \frac{2}{3}V_{dc}C_{dc}\frac{dV_{dc}}{dt} \right\} = i_d e_d + i_q e_q - R(i_d^2 + i_q^2) \qquad (14)$$

The left hand side of equation (14) is a power function in derivative model, integration of this function results in a energy function. Where

$$w_c = \int i_d L\frac{di_d}{dt} + i_q L\frac{di_q}{dt} + \frac{2}{3}V_{dc}C_{dc}\frac{dV_{dc}}{dt} \qquad (15)$$

$$w_C = \frac{L}{2}\left(i_d^2 + i_q^2\right) + \frac{1}{3}C_{dc}V_{dc}^2 \qquad (16)$$

IV. Design of Feedback Linearization Controller

There are two steps to design the Feedback Linearization control: nonlinear transformation into a linear system and design of linear controller

IV.1 Non Linear Transformation

Nonlinear transformation is a process to generate a linear input-output relation for a nonlinear active rectifier. An approach to obtain the input–output linearization of the MIMO system is to differentiate each output of the system until the inputs appear. By differentiating each output y in equation (9) by formula.

$$\dot{y}_i = L_f h_i + \sum_{j=1}^{2}\left(L_{gj}h_i\right)u_j$$

Where $L_f h$ and $L_g h$ represent Lie derivatives of h(x) with respect to f(x) and g(x), respectively. If $L_{gj}h_i(x)=0$ for all j, then the inputs do not appear and we have to differentiate repetively as

$$y_i^{(r_i)} = L_f^{r_i}h_i + \sum_{j=1}^{2}\left(L_{gj}L_f^{r_i-1}h_i\right)u_j$$

With $\begin{bmatrix} y_1^{(r_i)} \\ y_2^{(r_i)} \end{bmatrix} = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$ for at least one j.

If we perform the above procedure for each output y_i will be obtained as follows

$$\begin{bmatrix} \ddot{w}_c \\ \dot{i}_q \end{bmatrix} = A(x) + E(x)\begin{bmatrix} S_d \\ S_q \end{bmatrix}$$

Where

$$A(x)=\begin{bmatrix} L_f^{\,2}h_1 \\ L_f h_2 \end{bmatrix}=\begin{bmatrix} \frac{2R^2}{L}\left(i_d^2+i_q^2\right)+\frac{e_d}{L}\left(e_d-3Ri_d-\omega Li_q\right)+\frac{4}{3}\frac{V_{dc}^2}{R_L^2C_{dc}} \\ -\frac{R}{L}i_q+\omega i_d \end{bmatrix}$$

$$E(x)=\begin{bmatrix} L_{g1}L_f h_1 & L_{g2}L_f h_1 \\ L_{g1}h_2 & L_{g2}h_2 \end{bmatrix}$$

$$E(x)=\begin{bmatrix} \left(\frac{2R}{L}i_dV_{dc}-\frac{e_dV_{dc}}{L}-\frac{2}{R_LC_{dc}}i_dV_{dc}\right) & \left(\frac{2R}{L}i_qV_{dc}-\frac{2}{R_LC_{dc}}i_qV_{dc}\right) \\ 0 & \left(-\frac{V_{dc}}{L}\right) \end{bmatrix}$$

The matrix E(x) is called the decoupling matrix for the MIMO system. If the E(x) is nonsingular, then the input transformation can be obtained as

$$\begin{bmatrix} S_d \\ S_q \end{bmatrix}=E^{-1}(x)\left(\begin{bmatrix} v_1 \\ v_2 \end{bmatrix}-\begin{bmatrix} A_1(x) \\ A_2(x) \end{bmatrix}\right) \quad (18)$$

Where

$$E^{-1}(x)=\frac{1}{\frac{V_{dc}}{L}\left(e_d+\frac{2Li_d}{R_LC_{dc}}-2Ri_d\right)}\begin{bmatrix} -1 & \left(\frac{2L}{R_LC_{dc}}i_q-2Ri_q\right) \\ 0 & \left(2Ri_d-e_d-\frac{2L}{R_LC_{dc}}i_d\right) \end{bmatrix}$$

Substituting (18) into (17) results in a linear differential relation between the output y and the new input v

$$\begin{bmatrix} \ddot{w}_c \\ \dot{i}_q \end{bmatrix}=\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \quad (19)$$

IV.2 Design of Linear Control

After linear relation in equations (19) are obtained, then the controller for the linearized system can be designed. The DC voltage of active rectifier (V_{dc}) is controlled through energy function (w_c), then power factor and harmonic distortion is controlled through output Quadrature-axis current (i_q).

1. DC Voltage Control :

According Fig. 1. energy reference block (w_{Cref}) is produced from equations : energy definition (20), power balance (21) and unity power factor (22)

$$w_C^*=\frac{L}{2}\left(i_d^{*2}+i_q^{*2}\right)+\frac{C_{dc}}{3}V_{dc}^{*\,2} \quad (20)$$

$$\dot{w}_C^*=\frac{2}{3}\frac{V_{dc}^{*\,2}}{R_L}+e_di_d^*-R\left(i_d^{*2}+i_q^{*2}\right)=0 \quad (21)$$

$$i_q^*=0 \quad (22)$$

Substituting equation (20), (21) and (22) results in an energy reference as follow

$$w_C^*=\frac{L}{2}\left(\sqrt{\left(\frac{e_d}{2R}\right)^2+\frac{2}{3R}\frac{V_{dc}^2}{R_L}}+\frac{e_d}{2R}\right)^2+\frac{C_{dc}}{3}V_{dc}^* \quad (23)$$

Equation (23) depicts that the DC voltage reference V_{dc}^* should be determined.

The design of the tracking controller for the input v_1 is given by

$$v_1=\ddot{w}_c^*-k_{11}\dot{e}_w-k_{12}e_w \quad (24)$$

Where $e_w=w_c-w_c^*$ and the tracking error of the closed loop system as follows

$$\ddot{e}_w+k_{11}\dot{e}_w+k_{12}e_w=0 \quad (25)$$

To guarantee robustness and stableness against parametric uncertainty is added an integral error, so that (24) and (25) become

$$v_1=\ddot{w}_c^*-k_{11}\dot{e}_w-k_{12}e_w-k_{13}\int e_w dt \quad (26)$$

$$\ddot{e}_w+k_{11}\dot{e}_w+k_{12}e_w+k_{13}\int e_w dt=0 \quad (27)$$

Fig. 3 shows block diagram of linear control for the DC voltage

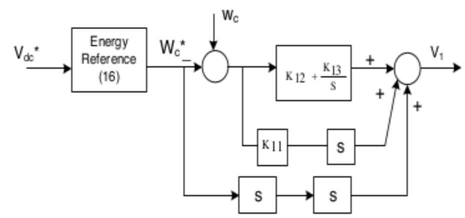


Fig. 3. Block diagram of the DC voltage control

2. Power Factor and Harmonic Distortion Control

To produce unity power factor and low harmonic distortion, reference value of quadratic-axis current is set to zero ($i_q^*=0$).

For tracking control, the new control input is given by

$$v_2=\dot{i}_q^*-k_{21}e_q \quad (28)$$

Where $e_q=i_q-i_q^*$, yields an exponentially stable tracking error

Then, the output errors become

$$\dot{e}_q+k_{21}e_q=0 \quad (29)$$

To guarantee robustness and stableness against parametric uncertainty is added an integral error, so that (28) and (29) become

$$v_2=\dot{i}_q^*-k_{21}e_q-k_{22}\int e_q dt \quad (30)$$

$$\dot{e}_q+k_{21}e_q+k_{22}\int e_q dt=0 \quad (31)$$

Fig. 4 shows block diagram of linear control for the power factor and harmonic distortion

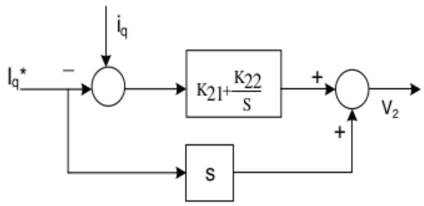


Fig. 4. Block diagram of power factor control

The gains kij are can be designed by Pole Plaement or linear quadratic regulator techniques, so that asymptotic tracking control to the reference is achieved. Fig. 5. show blok diagram of feedback Linearization.

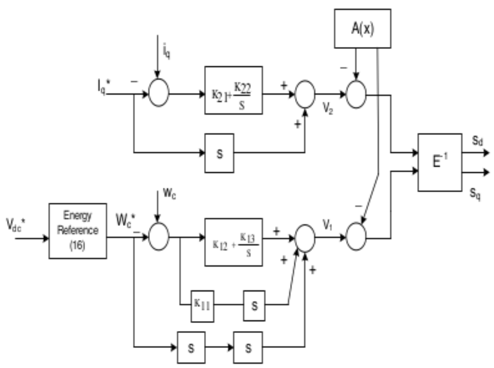


Fig. 5. Block diagram of Feedback Linearization Control

PI Optimized

An PI optimized system as shown in Fig. 6. is used to compare the performance of active rectifier with feedback linearization. The design of PI Optimized was aimed to tune the gains of the PI controller (Kp and Ki) and to optimize the response of the plant. The result simulation by using PI-optimized showed that proportional constant (Kp) was 3.18 and integral constant (Ki) was 5.024.

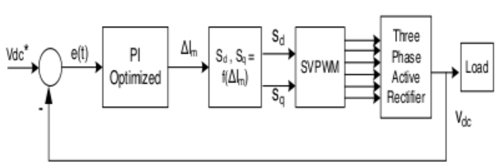


Fig. 6. Block diagram of PI Optimized controller

V. Result and Discussion

The proposed controller was evaluated through several simulations. This section present the most relevan results. The controller performance was tested through simulations on a system which system parameter can be seen in table 1.

TABLE 1
SYSTEM PARAMETER

Parameters	Value
DC Voltage (V_{dc})	650 volt
Amplitudo Source Voltage	√2 x 220 volt
Fundamental Frequency	50 Hz
Line Resistance	0.3 Ω
Line Inductor	8 mH
Filter capasitor	1000 uF
Frequency Switching	5000 Hz

Simulation results using the Feedback Linearization controller were compared to simulation using a PI optimized. The purpose of this comparison was to obtain high performance of the active rectifier system due to nonlinear effects.

Fig 7. presents the DC voltage of active rectifier with PI Optimized and Feedback Linearization controller. The PI optimized control methode produce the DC voltage with overshoot (Mp = 2%) and ripple 5.64 %., while the feedback linearization controller without overshoot and ripple with setling time 0.006 sec.

Fig.8. Demonstrates the line phase voltage and current. Fig 8a. the simulation results showed that line current produces transients respon until 0.1 sec, Total Harmonic Distortion (THD) = 10.42 % , Power factor =.0.92 for PI optimized. Fig. 8b. line current reaches steady state faster, THD = 0.21 % , Power factor = 1 for feedback linearization.

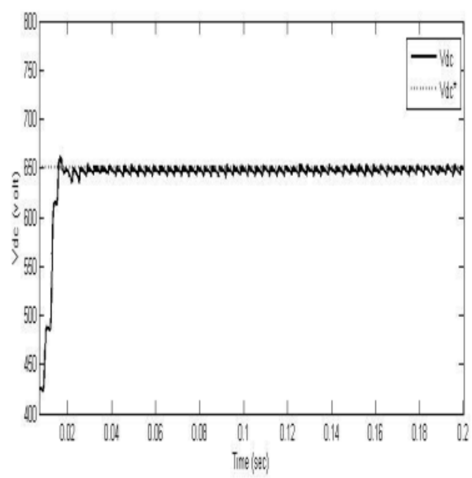
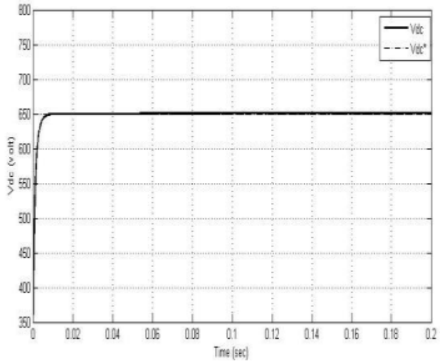


Fig.7.(a). Presents the DC voltage with PI Optimized



(b). The DC voltage with feedback linearization

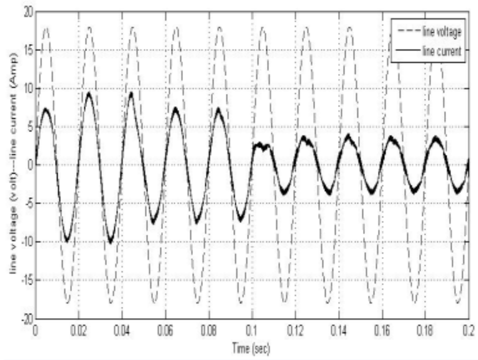


Fig. 8a. Demonstrates the line phase voltage and current of PI optimized

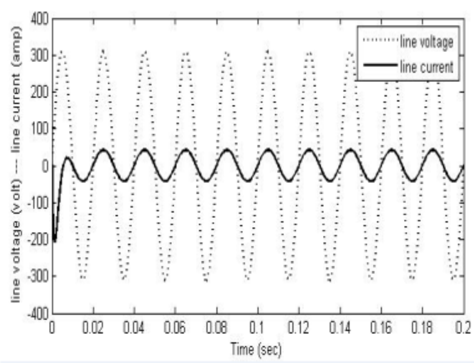


Fig. 8b. Demonstrates the line phase voltage and current of the proposed control

Fig 9. show the behavior under unbalanced conditions of the feedback linearization controller. An unbalance voltage with reducing amplitudo input voltage phasa A become 85% from the nominal voltage. Fig. 9a shows the active rectifier input voltages when the unbalance. Fig. 9b shows the DC voltage in the unbalance where is clearly seen small ripple voltage, however unity power factor is maintained (0.973).

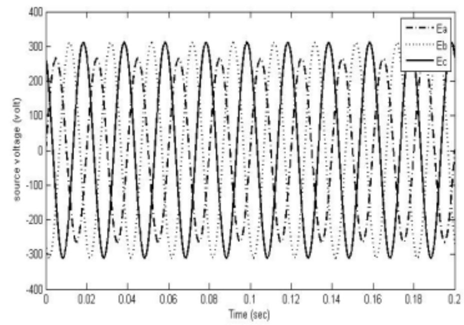


Fig. 9a shows the active rectifier input voltage

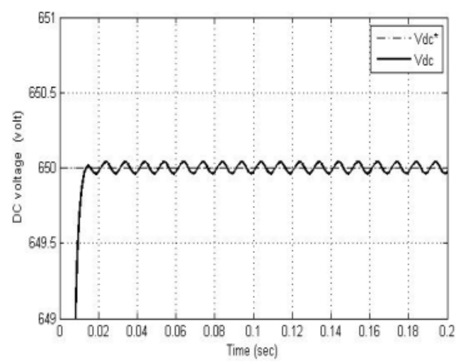


Fig. 9b. the DC voltage under the unbalance condition

VI. Conclusion

This paper presented high performance of nonlinear active rectifier using feedback linearization. The nonlinearity of the modeled system was eliminated by the proposed nonlinear control scheme such that avoided from internal dynamic so the linear control law can be used to control the system. This paper also presented to compare the simulation results with PI optimized. The simulation results showed that the feedback linearization controller had the best characteristics compared to PI optimized control methods, especially the DC voltage, power factor and THD in dealing with the nonlinearity behaviour..

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