Implementation of Effective Controllers for Negative Output Super Lift Luo Converter in DC Micro Grid Application

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***Abstract*— This article presents the modeling, simulation and design of effective controllers or dual loop controller for Negative Output Super Lift Luo Converters (NOESLLC) in continuous conduction mode (CCM) for DC microgrid application that are attractive owing to the inclusion of renewable energy sources. Owing to the small output voltage of these DC sources, super lift Luo Converters is essential to fix a DC source in DC microgrid. Traditional boost converter, buck converters, SEPIC and buck-boost converters have produced less voltage transfer gain and more ripples. With the aim to overcome these crisis's, NOESLLC is proposed for DC micro grid application. The load voltage and inductor current of the NOESLLC is regulated using effective controller loops. It consists of Proportional Integral (PI) controller acting as outer voltage loop for the load voltage regulation and P controller act as inner current loop to regulate the coil current. The dual loop controller for NOESLLC is verified by developing the MATLAB/SIMULINK model at different operating conditions.**

***Index Terms*— Luo Converters, DC microgrid**

I. Introduction

In current scenario, DC-DC converters play a vital role in various applications such as renewable energy, LED TV, battery charging, medical equipment, electric traction, electric vehicles etc., For these applications, it is essential to have good output voltage regulation, minimized current/voltage stresses, reduced ripples of voltage and current. Due to theses constraints, many of the DC-DC converter topologies have been developed such as buck, boost, buck-boost, single ended primary inductance converter (SEPIC), KY converters and Luo-converters (LCs) [1-3]. Among these topologies, LCs being more suitable for high voltage applications show good voltage transfer ratio, good power density, reduced ripples of voltage and inductor current. The recently derived DC-DC LCs converters are discussed [4]. It has three techniques namely voltage lift, super lift and ultra-lift. In this paper, super lift technique (SLT) is used. The SLT increases the output voltage transfer gain in geometry progression. The SLT can be subdivided into (POSLLC), (NOSLLC), cascaded POBC and cascaded NOBC respectively. The controller design is challenging one for LCs [5]. Therefore, in this article, the design of effective controllers for Negative Output Elementary Super Lift Luo Converter (NOESLLC) is investigated. The open loop study of cascaded boost converters has been reported in [6]. But, the efficiency of the same converter is around 78%. The design of parallel operation of cascaded boost converters with PI controller is well reported in [7]. However, the ripple with this controller have produced 0.02V and efficiency of 95%. Also, verification is not carried out for different line and load variation using designed controllers. Small signal modelling analysis of traditional double boost converter and SEPIC have been addressed in [8].

The design of sliding mode controller (SMC) for a modified boost Cuk converter topology is well presented in [9]. But the experimental part is not analysed for designed converter using SMC. Also, ripples of same converter have produced around 0.9V during the simulation study. Multi-stage cascaded DC-DC converters for PV applications are well executed in [10]. In this article, only the simulation study has been carried out for the converter designed for solar system. Double loop control structure for boost converter is presented in [11]. The simulation analysis has been carried out for boost converter with SMC, PI and SMC plus PI at different operating conditions. Application for battery charging/discharging and fuel cell/solar system using SMC has been recorded in [12]. In this article, the complete simulation and the experimental analysis parts have been reported. A unified model of restructured conventional controllers such as buck, boost and buck-boost converter with its controller is reported in [13]. Dual classical linear control for boost converter has been addressed in [14]. However, the linear controllers are not capable to regulate the output voltage during large line variations.

Experimental analysis of novel SMC for DC-DC boost converter is well reported in [15]. Yet, the new SMC control law is discussed in this article. Multilevel cascaded converter with boosting technique is well reported in [16]. SMC and proportional double integral controller (PDIC) for many LCs topologies have been addressed in [17]-[20]. However, the controller implementation for these converters needs many mathematical calculations and more number of sensors. Fuzzy logic controller (FLC) is one of the intelligent or non-linear controller (NLC) structures [21]. FLC rules are arrived from system performance parameters and also, it is designed without mathematical modelling of the system which leads to reduced calculation and sensors. Design of FLC for various DC-DC converters has been recorded in [22]-[35]. Most of the research articles have not discussed dual loop controllers (DLC) for NOESLLC in continuous conduction mode (CCM). In this article, the design and implementation of DLC for NOESLLC in CCM has been carried out.

II. Operation and Modelling of NOESLLC

A. Converter Operation

The power circuit diagram of the NOESLLC is shown in Fig.1. The proficient voltage step-up capability can be attained by controlling the power switch Q of the NOESLLC.

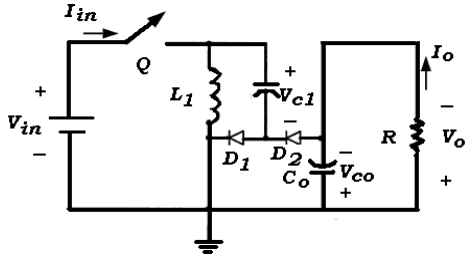


Fig. 1 Power circuit of NOESLLC

In the power circuit, V_{in} is a DC input supply voltage, Q is the power switch (n-channel MOSFET), and D_1 and D_2 are freewheeling diodes. Energy storage elements are capacitors (C_1 and C_o) and inductor L_1. V_O is the output voltage and R is the load resistance. It is assumed that all the components are ideal and in addition, the NOESLLC operates in CCM.

To study the operation of the NOESLLC, the circuit can be divided into two states, viz. the switch-ON state and the switch-OFF state. Fig.2 and Fig. 3 show the two states of operation of the NOESLLC as discussed by Fang Lin Luo and Hong Ye (Fang Lin Luo and Hong Ye, 2003).

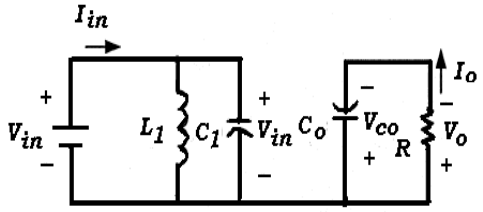


Fig. 2 Mode 1 operation of NOESLLC

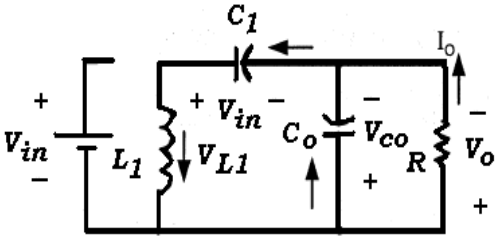


Fig. 3 Mode 2 operation of NOESLLC

In state 1 operation, the switch Q is in ON state, the diode D_1 conducts. The capacitor C_1 is charged by supply voltage V_{in} in short duration of time period and this capacitor voltage is assumed as a steady value. The current through the inductor (L_1), i_{L1} rises due to V_{in}. The output capacitor, C_o provides the energy to the output load. The equivalent circuit of mode 1 operation of NOESLLC is illustrated in Fig. 2.

During the state 2 operation, switch Q is in OFF state, diode D_2 conduct and hence, the inductor current decays with the C_1 voltage (V_o-V_{in}) to provide the energy to C_o and load branch. The equivalent circuit of NOESLLC in mode 2 is shown in Fig.3. The ripple of the inductor current i_{L1} may be written as

$$\Delta_{iL1}=\frac{V_{in}}{L_1}dT=\frac{V_o-V_{in}}{L_1}(1-d)T \tag{1}$$

Where d is the duty cycle and T is time period. The voltage transfer gain is

$$G=\frac{V_O}{V_{in}}=\frac{2-d}{1-d}-1 \tag{2}$$

In constant state, the average charges across capacitor, C_o in a period should be zero and it can be expressed as

$$\begin{aligned} dT\, i_{Co\text{-}on} &= (1-d)T i_{Co\text{-}off} \\ i_{Co\text{-}on} &= I_o \end{aligned} \tag{3}$$

Where $i_{Co\text{-}on}$ is C_o current during on state and $i_{Co\text{-}off}$ is C_o current during off state. The variation ratio of inductor current is

$$\xi=\frac{\Delta_{iL1/2}}{i_{L1}}=\frac{d(1-d)TV_{in}}{2L_1I_o}=\frac{d(1-d)}{G}\frac{R}{2f_sL_1} \tag{4}$$

The ripple voltage of output voltage, V_o is

$$\Delta V_o=\frac{\Delta Q}{C_o}=\frac{I_o(1-d)T}{C_o}=\frac{(1-d)}{f_sC_o}\frac{V_o}{R} \tag{5}$$

Therefore, the variation ratio of output voltage is

$$\xi=\frac{\Delta V_O/2}{V_o}=\frac{(1-d)}{2Rf_sC_o} \tag{6}$$

As seen, the voltage transfer gain for a single stage is more than that obtained for classical converters that can be clearly observed in the graphical representation diagram in Fig.4.

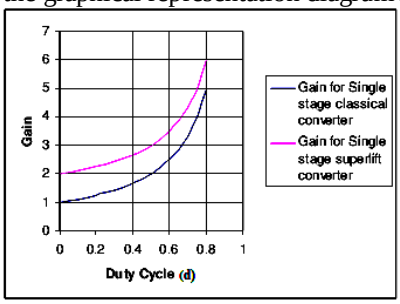


Fig. 4 Comparison of voltage transfer gain for NOESLLC and classical converter

B. Modelling of Converter

From the Fig.2, the state-space equation of it can be engraved as (7)

$$\begin{cases} L_1\dfrac{di_{L1}}{dt}=V_{in} \\ C_o\dfrac{dV_o}{dt}=-\dfrac{V_o}{R} \end{cases} \quad \text{Switch -ON} \tag{7}$$

From the Fig. 3, the state-space equation is written as (8)

$$\begin{cases} L_1 \dfrac{di_{L1}}{dt} = V_{in} - V_o \\ C_o \dfrac{dV_o}{dt} = i_{L1} - \dfrac{V_o}{R} \end{cases} \quad \text{Switch -OFF} \qquad (8)$$

Using the capacitor charge balance rule on C_1, the whole switching time period is obtained from the equation (9), where d is the status of the switch (d = 1 when the switch is ON, and d = 0 when the switch is OFF).

$$\text{Switching time} = dC_1 \frac{dV_{C1}}{dt} + (1-d) i_{L1} \qquad (9)$$

By choosing the state space variables of converter (say inductor current and output voltage). By using (7)–(9), the state-space average modeling of the NOESLLC can be written as (10)

$$\begin{bmatrix} i_{L1} \\ V_o \end{bmatrix} = \begin{bmatrix} 0 & -\dfrac{1-d}{L_1} \\ \dfrac{1-d}{C_o} & -\dfrac{1}{RC_o} \end{bmatrix} \begin{bmatrix} i_{L1} \\ V_o \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L_1} \\ 0 \end{bmatrix} V_{in} \qquad (10)$$

$$A = \begin{bmatrix} 0 & -\dfrac{1-d}{L_1} \\ \dfrac{1-d}{C_o} & -\dfrac{1}{RC_o} \end{bmatrix},$$

$$B = \begin{bmatrix} \dfrac{1}{L_1} \\ 0 \end{bmatrix},$$

$$C = \begin{bmatrix} 0 & 1 \end{bmatrix},$$

$$D = 0 \qquad (11)$$

Where, A, B, C and D are averaged state-space matrices of NOESLLC.

C. Design Computation of the NOESLLC Circuit Components

The NOESLLC elements are designed with the following specifications as shown in Table 1.

III. Open Loop Simulation Analysis of the NOESLLC

In this section the design of NOESLLC in open loop is discussed. The MATLAB/Simulink model of NOESLLC is simulated as per the specification listed in Table 1.

TABLE I
SPECIFICATIONS OF NOESLLC

Symbol	Parameter Name	Value
V_{in}	Input Voltage	12V
V_o	Output Voltage	-36V
L_1	Inductor	100μH
C_1,C_o	Capacitors	30 μF
fs	Nominal switching frequency	100kHz
R	Load resistance	50Ω -60Ω -
P_o	Output power	25.92W
P_{in}	Input power	28.236W
I_{in}	Input current	2.353A
η	Efficiency	91.8%
I_o	Output current	-0.72 A
d	Duty cycle	0.667
ΔVo	Capacitor ripple voltage	-0.16V
Δ_{iL1}	Inductor ripple current	0.6A

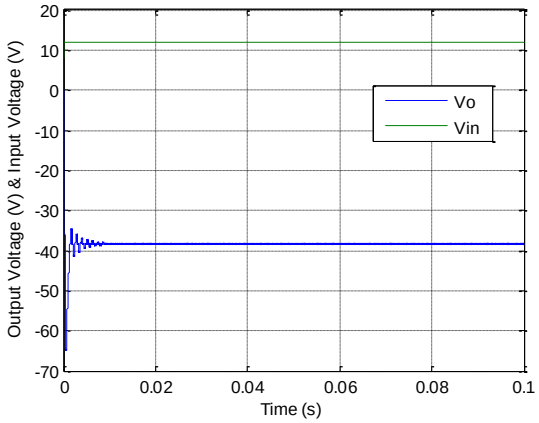


Fig 5 Transient response of NOESLLC without controller

The fig. 5 shows the variation of input voltage and output voltage with respect to time for normal operating condition i.e without any disturbance to the system. Even without any disturbance it has an initial peak overshoot of about -28V large output voltage ripple is visible very clearly.

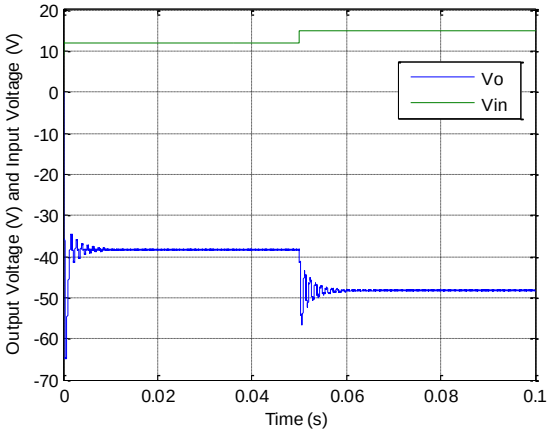


Fig 6 Input voltage variation of NOESLLC without Controller

With line variation from 12V to 15V the output voltage is disturbed and a very large overshoot is seen. This means that the output voltage is not in regular form as shown in fig.6.

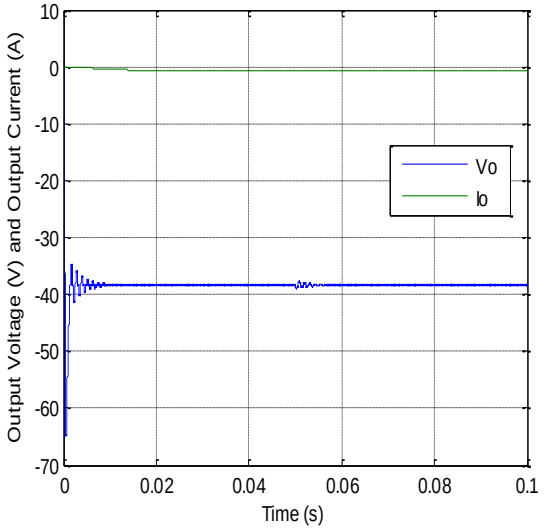


Fig. 7 Output Voltage when load changes from 50 to 60 Ohms

This open loop NOESLLC output voltage is also affected by the sudden change in load due to unexpected change of variation system disturbance. In general the experts mention this change of system parameters as parasitic effect. One such kind is load disturbance which viewed in the below fig.8 with sudden change in load from 50 ohms to 60 ohms. On seeing the fig 8 the output voltage is disturbed with small overshoot and change in output voltage.

From fig.8 the output power=26.34 W, input power=28.86 W and the maximum efficiency of 91.27% for NOESLLC under normal operation condition without use of any feedback controller.

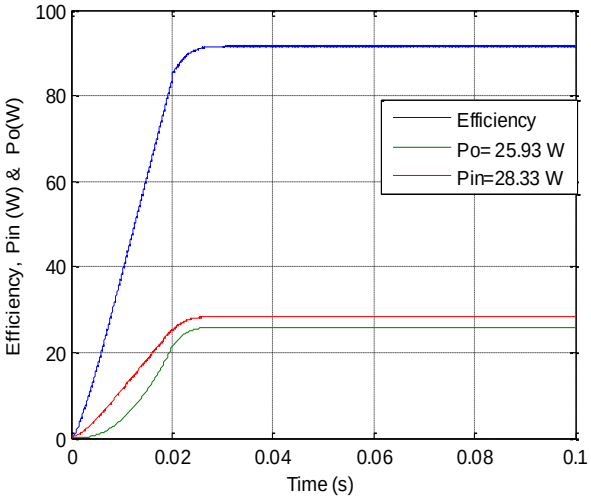


Fig 8. η , i/p and o/p Power of NOESLLC without controller

IV. Design of Dual Loop Controller for NOESLLC

This section deals about the dual controller design for NOESLLC to regulate the output voltage and inductor current. A PI controller is chosen for providing the better output voltage regulation in NOESLLC. The DC output voltage is sensed and compared with reference output voltage, and error signal is obtained. This error signal is processed by the PIC to maintain the output voltage constant. The PIC parameters, proportional gain (K_p) and integral times (T_i), are obtained by using Zeigler – Nichols tuning method.

The transfer function (T.F) model of equation (11) is obtained from the state space average model of equation (12) using MATLAB. Then,

$$T.F=\frac{-7.958e^{-12}\ s^2\ +1.667e^8 s+1.389e^{12}}{s^3\ +666.7\ s^2\ +8.333e^7 s} \quad (12)$$

For simplicity in the design aspect, the term $-7.958e^{-12}s^2$ in the numerator of the T.F model is very small and hence it can be neglected. Therefore, the T.F becomes

$$T.F=\frac{1.667e^8 s+1.389e^{12}}{s^3\ +666.7\ s^2\ +8.333e^7 s} \quad (13)$$

The characteristics equation with proportional control is expressed by

$$s^3+666.7\ s^2+s\ (8.333e^7+K\ 1.667e^8)+K\ 1.389e^{12}=0 \quad (14)$$

The Routh array of equation (14) is

s^3 : 1 $(8.333e^7+1.667e008\ K)$

s^2 : 666.7 $1.389e^{12}\ K$

s^1 : $(-8.333e^7+2247116969\ K)$

s^0 : $1.389e^{12}\ K$

From this routh array, the range of K for stability is $(-8.333\ e^7+2247116969\ K) > 0$, $K > 0.037$, $0 < K < 0.037$. So, the ultimate critical gain K_{cr} = 0.037, and their corresponding ω_n =210447 rad/sec and P_{cr}=2*piω_n =$2.9856e^{-5}$.

After tuning the controller using this method, the NOESLLC reaches expected steady state with few oscillations, where the ultimate gain for stability can be found as K_{cr}=0.02 and their corresponding ultimate period as P_{cr}=0.0012s. Using this method the values of K_p=0.01105 and T_i=0.01233s are determined.

V. Simulation, Results and Discussion

This section briefly describes the implementation of dual loop controller for NOESLLC in DC micro grid application. The output voltage is compared with the reference voltage and the error e_1 is fed to the PI controller. Reference currents are generated using the output of the PI controller. The instantaneous values of actual current and reference current are compared and the error is found to be e_2.The inputs to the P controller are voltage error e_1 and the current error e_2. The output u is the control signal , which in turn sets the new duty ratio of the switching pulses for triggering the switch of the NOESLLC.

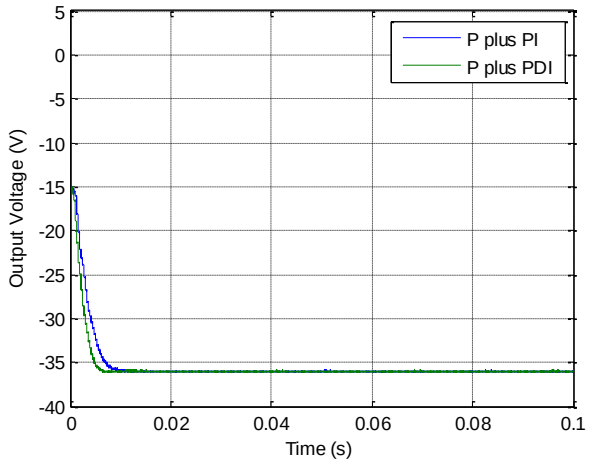


Fig.9 Simulated output and input voltage responses o NOESLLC in transient region using dual loop controller

Fig. 9 shows the simulated output voltage and input voltage for NOESLLC in DC micro grid application using dual loop controller. It is found that output voltage response of the same converter using controller has produced null overshoots and quick settling time.

A. *Line Variation*

Fig. 10 show the simulated output voltage and input voltage responses of this converter using designed controller for input voltage change from 12V to 15V. From this results, it is found that the output voltage response of this converter has produced 4V peak overshoots and settling time of 0.01s.

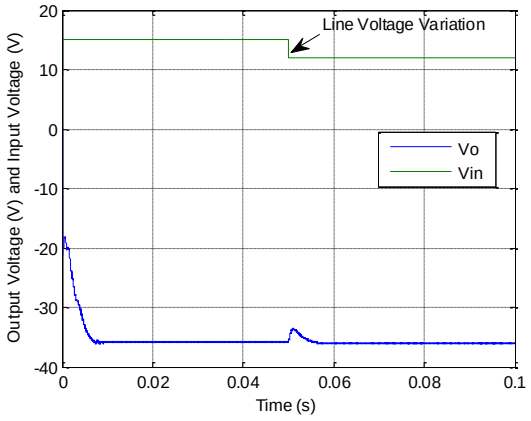
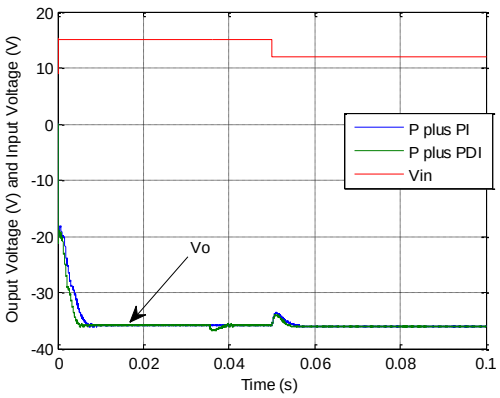


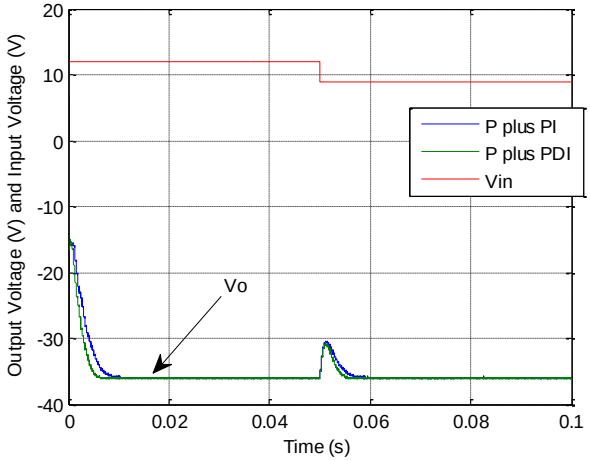
Fig.10 Simulated output voltage response for NOESLLC with dual loop controller during line variation

B. *Load Variation*



(a) load change from 50 ohm to 60 ohm

Fig. 11 shows the simulated output voltage and load current responses of this converter using designed controller for load change from 50 ohm to 60 ohm. From these results, it is found that the output voltage response of this converter has produced 2V peak overshoots and settling time of 0.005s.



(b) load change from 50 ohm to 40 ohm

Fig.11 Simulated output voltage response for NOESLLC with dual loop controller during load variation

C. *Circuit Components Variations*

The circuit parameters such as inductance and output capacitance is varied for the NOESLLC along with the closed loop controller is shown in the fig 12 and fig 13 for certain time interval.

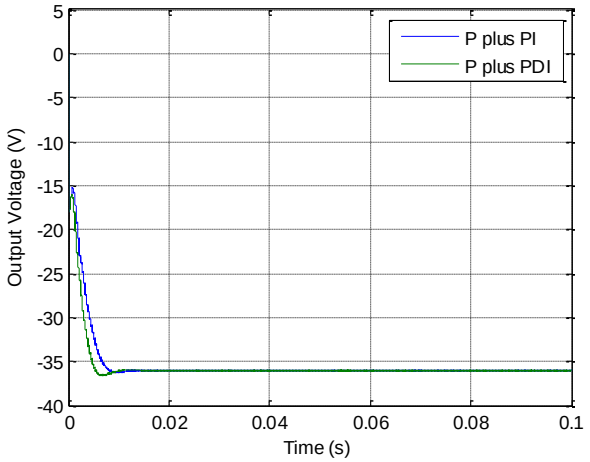


Fig 12. Regulated o/p voltage when C_o changes from 30 to 80 μ F

The fig 12 shows the regulated output voltage when the output capacitance changes from 30 to 80 μ F. Its output voltage and output current does disturbed because of the usage of the closed loop controller for a particular line voltage.

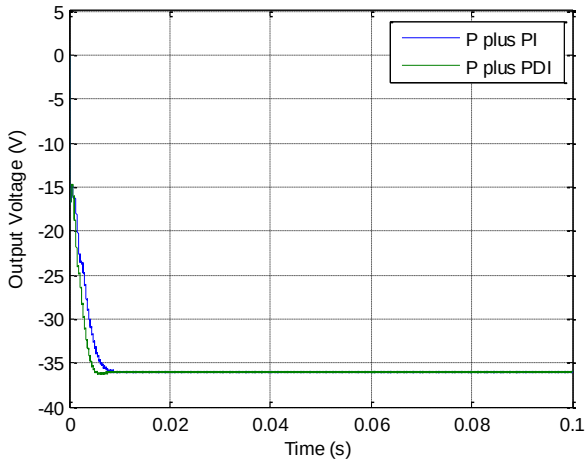


Fig 13. Regulated o/p voltage when L changes from 100 to 200 μ H

Similarly fig. 13 shows the regulated output voltage for the input inductance changes from 100 to 200 μ H. Its output voltage and output current is disturbed because dual loop controller for NOESLLC for a particular line voltage.

D. Steady State Region

For a particular line voltage the fig 14, shows output capacitor and inductor current ripple of NOESLLC using designed controller.

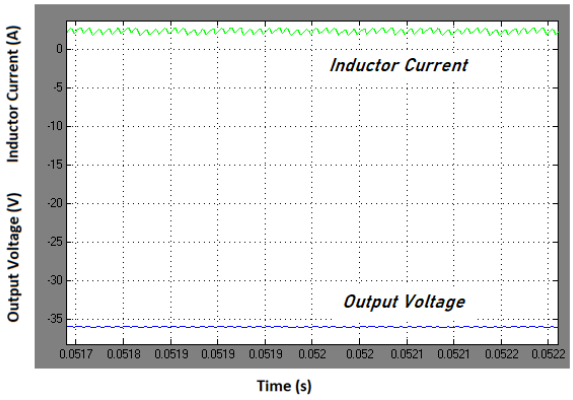


Fig 14. Output capacitor voltage ripple for NOESLLC with dual controller

For the certain range of load resistance the efficiency is plotted for NOESLLC with controller for line voltage 12V with no circuit parameter variation as shown in fig 15.

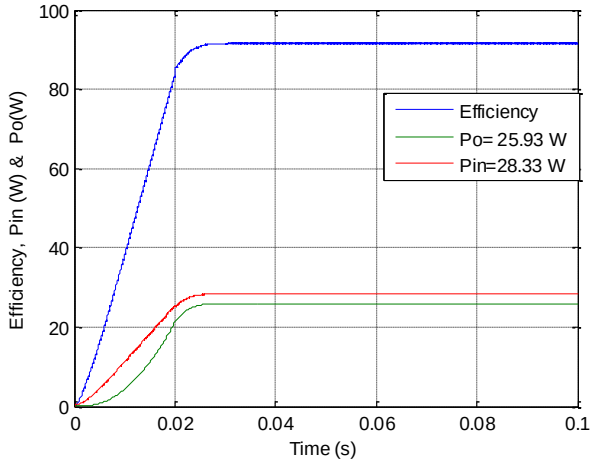


Fig 15. Percentage eEfficiency for various load change of NOESLLC with controller

The input voltage Vs output voltage of NOESLLC with controller is depicted in the fig.16 which is having negligible overshoot.

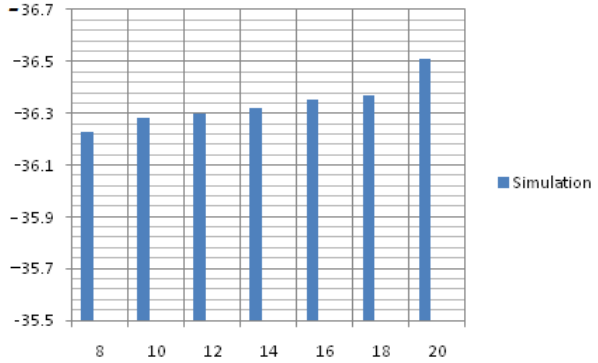


Fig 16. Input voltage vs output voltage

The results obtained from different variation in line and load are shown in table II

TABLE II
RESULT COMPARISON

		P plus PI	P plus PDI
Start up-Region	M_p	-	-
	$T_{s\,(s)}$	0.01	0.008
Line Variations V_{in}=12Vto 09V	M_p	-4.5V	-4V
	$T_{s\,(s)}$	0.008	0.0065
Line Variations V_{in}=12Vto 15V	M_p	-4.5V	-4V
	$T_{s\,(s)}$	0.008	0.0065
Load Variations R=50Ω to 40Ω	M_p	-2.2V	-2V
	$T_{s\,(s)}$	0.008	0.005
Load Variations R=50Ω to 60Ω	M_p	-2.2V	-2V
	$T_{s\,(s)}$	0.008	0.005

VI. CONCLUSIONS

Thus the modeling, simulation and design of dual loop controller of NOESLLC for DC micro grid application have been successfully demonstrated in MATLAB/Simulink software platform. Dual loop consist of PI controller (outer loop) and P controller (inner loop) and its parameters are computed using Ziegler-Nichols tuning method. Many simulation results are presented to prove the proficient of the designed controller. It is more suitable for DC micro grid application and for low power application such as power supply for various medical equipments, communication system, computer hardware parts and industrial application.

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