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Stability and Dynamic Response of Analog and Digital Control loops of Bidirectional buck-boost Converter for Renewable Energy Applications

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***Abstract*: This article presents the stability and dynamic response of open loop and closed loop control of Bidirectional buck-boost converter(BBC) using PID and PIDN controllers through transfer function model implemented in MATLAB code. In order to ensure the stability of switch mode power supplies the control loop behaviors need to be characterized. Improvement of stability of BBC using PID/PIDN compensators is demonstrated in both analog and digital domains by plotting bode plots. Step response of BBC using PID /PIDN controllers are plotted that defines the dynamic behavior of the system.PIDN compensator is proposed to maintain a healthy balance between the stability and transient behavior since both are indirectly proportional.**

***Index Terms*: Analog and digital control loops, Bidirectional buck-boost converter, Bode plots, Dynamic response ,PID,PIDN, Stability analysis .**

I. INTRODUCTION

Now a days renewable energy sources are more in demand to save the environment and hence storing the energy is also increased. The Bidirectional buck-boost converter(BBC) as power interface between main and auxiliary energy storage become key element[13]-[15].In many applications like Hybrid electric vehicles(HEVs),fuel cell electric vehicles(FCEVs), stand-alone PV power plants, automotive industries and so on, the bidirectional buck-boost converter plays very important role for efficient usage of power and to improve the stability and flexibility of the system. The best application of BBC is in electric vehicle where it captures the kinetic energy of motor and charging the battery during regenerative braking by reverse flow of energy as shown in fig.1[19]-[23].Similarly there are some hybrid renewable energy system as shown in fig.2 where solar energy, wind energy etc. are environment dependent systems therefore fluctuation of output power and sudden change in load demand results in unreliable system .The solution for this issue is usage of storage system like battery with the help of BBC for power conditioning and smooth flow of power to the load. High power and medium/high-voltage energy conversion system offers modularity, voltage/current scalability, transformer less operation, fault
blocking capability, reduced filter size, reduced size, high efficiency and low expense on duplication[16]-[18]. Stability and dynamic response of BDC play very important role for the existence of the systems discussed earlier where BDC is used. Bode plots are used to measure the stability of such power converters in terms of gain margin , phase margin and bandwidth of control loops in frequency domain.

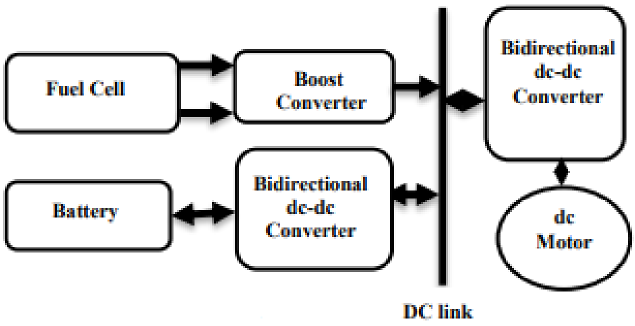

Fig.1.Fuel cell powered electric vechicle

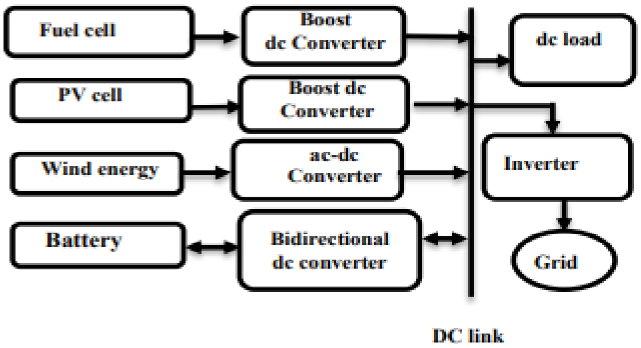

Fig.2. Hybrid Energy System with Battery Interface using Bidirectional dc-dc Converter

II. BIDIRECTIONAL DC-DC CONVERTER

The bidirectional buck-boost converter with resistive load at one side and battery bank at the other side is as shown in fig.3.Mathematical Modeling is performed under continuous conduction mode using state space average large signal modelling.Modeling is carried out separately for boost mode as well as buck mode of operations.

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During boost mode of operation switch ‘S_2’ is working along with the diode which antiparallel with switch ‘S_1’.In this mode of operation, the voltage source is Vbatt and the load is resistive load (R) as shown in fig.3.Circuit is switched to boost mode when the bus voltage ‘Vbus’ goes below the voltage required by the ‘R’load .In this mode ,the battery is in discharging mode. Circuit switched to buck mode when the bus voltage is sufficient to provide the voltage required by the load ‘R’ .In this mode the battery is in charging mode. During buck mode of operation switch ‘S_1’ is working along with the diode which is antiparallel with switch ‘S_2’.

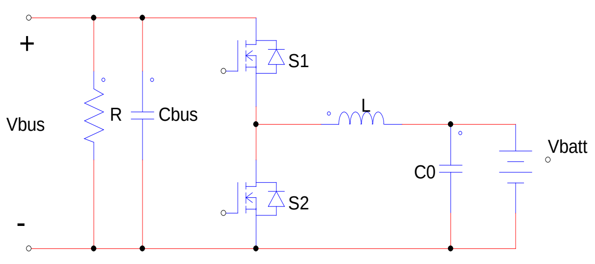

Fig.3 bidirectional buck-boost converter

Table I. Specifications of BBC

Parameter	Value
DC Bus voltage (Vbus)	24V
DC Bus current (I_{bus})	3 A
Battery voltage (V_{Batt})	12 V
Switching frequency (F_s)	20 KHz
Load voltage (V_0)	24 V
Load Current (I_0)	2.4 A
Duty Cycle (d)	0.5
Inductor (L)	1000 µH
DC bus capacitor (C_{bus})	250 µF
Load resistor (R)	10 Ω
Capacitor across battery (C_0)	125 µF
Battery resistance (R_{batt})= $\frac{Ns}{Np}$*R_{inter} = $\frac{6}{1}$*30 m Ω	0.18 Ω

III. Modeling

During Boost mode of operation of BBC, the state equations are shown by eqn (1) and output equations are shown by eqn (2).

$$\begin{bmatrix} x_1' \\ x_2' \end{bmatrix} = \begin{bmatrix} 0 & -\frac{(1-d)}{L} \\ \frac{(1-d)}{C_{bus}} & -\frac{1}{RC_{bus}} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{batt} \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{batt} \ldots\ldots\ldots\ldots\ldots(2)$$

During Buck mode of operation of BBC, the state equations are shown by eqn (3) and output equations are shown by eqn (4).

$$\begin{bmatrix} x_1' \\ x_2' \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C_0} & -\frac{1}{R_{batt}C_0} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix} Vbus \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{bus} \ldots\ldots\ldots\ldots\ldots(4)$$

Considering the design specifications given in the table I, the transfer function of boost mode (TF_{boost}) is obtained using eqns (1) and (2) and it is shown in eqn (5) also the transfer function of buck mode (TF_{buck}) is obtained using (3) and (4) and it is shown in eqn (6) .

$$TF_{boost} = \frac{2*10^6}{S^2 + 400S + 1*10^6} \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

$$TF_{buck} = \frac{4*10^6}{S^2 + 4.444*10^4 S + 8*10^6} \ldots(6)$$

Stability analysis is performed in open loop as well as closed loop control of each mode of operation in both analog as well as digital domain. For digital domain implementation, transfer function of analog domain is converted into digital domain using Tustin transformation technique and it defines redesign digital control method. Digital transfer functions of BBC in boost and buck modes are shown in eqns (7) and (8) respectively using Tustin transformation with sampling time ‘t’ =01 sec.

$$G(Z)_{boost} = \frac{4.9899*10^{-05}\ (z+1)^2}{(z^2\ - 1.996z + 0.996)} \ldots\ldots(7)$$

$$G(Z)_{buck} = \frac{0.4501\ (z+1)^2}{(z+0.8007)\ (z+0.9991)} \ldots\ldots(8)$$

IV. Stability and Dynamic Response

Stability and dynamic response analysis are carried out for BBC in open loop and closed loop control in analog and digital domain .Closed loop control is designed with PID and PIDN controls with gain values which are obtained by auto tuning of transfer function model of each mode of BBC in MATLAB tool.

Stability and dynamic response of BBC in two modes of operation are as follows.

(i) Stability and dynamic response in Boost mode.

PID control gains: `kp=4.63 ,ki=1039.4 ,kd=0.0048 , N=1703100.`

`PIDN` control gains: `kp=4.63 ,ki=1039.4 ,kd=0.0048 , N=17031.`

(ii) Stability and dynamic response in buck mode.

PID control gains: `kp=3.14 ,ki=921.8 , kd=-0.0048 ,N=778000.`

`PIDN` control gains: `kp=3.14 ,ki=921.8 , kd=-0.0048 ,N=778.`

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4.1 Stability and dynamic response in Boost mode

The transfer function model of BBC in boost mode is shown in eqn(5) and it is implemented using text based computational implementation in matlab code. This allows the BBC in boost mode model to easily embed in design,simulation,analysis and education application software. Text based computational implementation basically translates the differential equations into discrete programming code. Using MATLAB code Eqns (1) and (2) are used to obtain transfer function as shown in eqn (5) using function ss2tf() .By making use of transfer function, step response, bode plot are obtained for BBC in open loop and closed loop with PID/PIDN control in boost mode.

4.1.1. Dynamic response

Step response which reveals the dynamic response of BBC in boost mode is as shown in fig.4.Dynamic characteristics of BBC for step input is listed in the table-II.PIDN control performs action as same as PID but also perform filter action for the output generated by the differentiator Hence it's called PIDN.Filter eliminates the noise in the output signal of differentiator which amplifies load signal along with the noise .PIDN control obtains ripple free load signal which results in better stability. From the data listed in the table.II,it is understood that PIDN control loop gives better tradeoff between stability and dynamic response whereas PID control gives only better dynamic response but not better stability than PIDN.

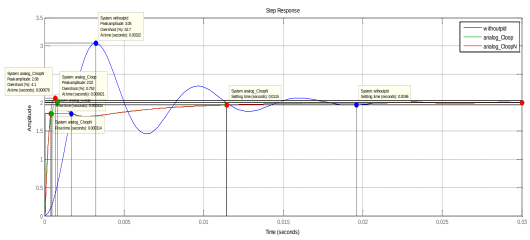

Fig.4. Step response of BBC in Boost mode with PID,PIDN and without PID control for 50% duty cycle.

TABLE II. Step response of BBC with PID ,PIDN and without PID in boost mode

BBC	Peak amplitude in volts	Overshoot	Rise Time in seconds	Settling time in seconds
Open loop	3.05	52.7%	0.00121	0.0196
With PID	2.02	0.735%	0.000416	0.0114
PIDN	2.08	4.1%	0.000414	0.0115

4.1.2. Stability

Frequency response gives the information about the control loops. In a perfect control loop, the output voltage would remain locked to the reference voltage even if the load or input voltage changes.The frequency response indicates how a switching regulator will react under defined operating conditions across a range of frequencies. The frequency response is a dynamic model of the system showing how variations in the input voltage, the load and duty cycle affect the output voltage according to frequency. The frequency response Influences the reaction time, precision and stability of the system. The frequency response of BBC in boost mode in analog domain is s shown in fig.5 can be determined from transfer function using bode plots which is basically a graph of magnitude and phase of the transfer function as a function of frequency, where magnitude is plotted in decibels and phase in degrees. These plots revel some key Information about the control loop's performance. The first point of interest is the crossover frequency (fc). Here ,BBC in boost mode is showing 9.13 KHz under PIDN control. This is the frequency at which the control loop gain is unity (0 dB) and is also referred to as the loop bandwidth. The second point of interest is the place at which the phase lag reaches 180^0 .In this case ,its infinity under PIDN control. The phase margin (PM) equals 180^0 minus the phase lag at fc. In this case its 82.6^0.The gain margin (GM) is the gain at a phase lag of 180^0.In this case its infinity under PIDN control. The system will be stable if the phase lag at fc is less than 180^0.Here in buck mode under PIDN control, its 82.6^0 therefore its stable. For most control loops, the engineers aim to achieve a PM greater than 45^0 and less than 180^0 .Typically, a phase margin of 45^0 provides good transient response with good damping. For buck or boost switching system the gain margin should be above 10dB.In this case,GM is infinity. The data which defines the stability of BBC in boost mode with PID and PIDN control loops is extracted from bode plots of analog domain which is as shown in fig.5 and is tabulated in the Table .III. Similarly the data which defines the stability of BBC in boost mode with PID and PIDN control loops is extracted from bode plots of digital domain which is as shown in fig.6 and is tabulated in the table .IV.

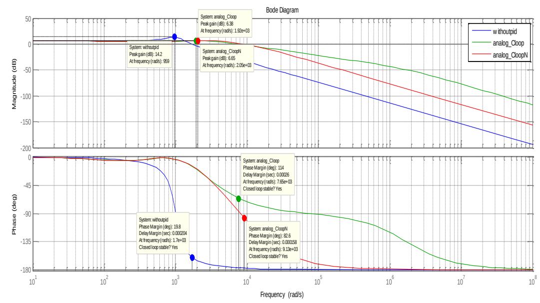

Fig.5. Frequency response of BBC with PID,PIDN and without PID control in boost mode.

TABLE III. Comparison of stability analysis in analog domain of BBC in boost mode of operation

System	PM (degrees)	GM (db)	ω_g (rad/sec)	ω_p (rad/sec)	Delay Margin (sec)	Stability state
Open loop	19.8	Inf	Inf	1700	0.000204	Stable with poor dynamic response
with PID control	114	Inf	Inf	7650	0.00026	stable
with PIDN control	82.6	Inf	Inf	9130	0.000158	stable

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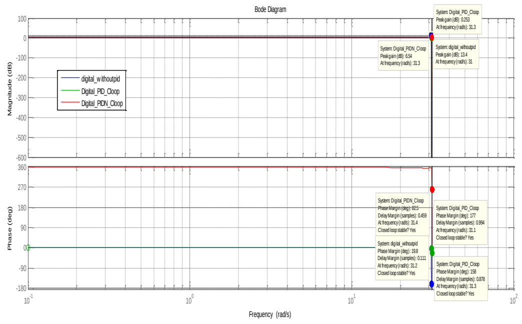

Fig.6. Digital domain- Frequency response of BBC with PID,PIDN and without PID control in boost mode.

TABLE. IV. Comparison of stability analysis in digital domain of BBC in boost mode of operation .

System	PM (degrees)	GM(db)	ω_g (rad/sec)	ω_p (rad/sec)	Delay Margin (samples)	Stability state
Open loop	19.8	Inf	Inf	31.5	0.111	Stable with poor dynamic response
with PID control	177 & 158	Inf	Inf	31.1 & 31.3	0.994 & 0.878	Stable
with PIDN control	82.5	Inf	Inf	31.4	0.459	stable

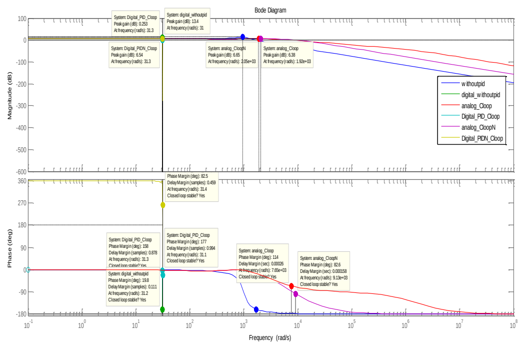

Fig.7. Mixed domain - Frequency response of BBC in boost mode in open loop, closed loop with PID and PIDN.

4.2. Stability and Dynamic response in buck mode

The frequency response of a BBC with and without compensator in buck mode is determined using transfer function . Eqns (3) and (4) are used to obtain transfer function as shown in eqn (6) using function ss2tf() .By making use of transfer function, step response, bodeplot and pole & zero plot are obtained for BBC with PID,PIDN and without PID control in buck mode.

4.2.1. Dynamic response

Step response gives transient and steady state response of the system that define dynamic response. The dynamic response of BBC in buck mode is as shown in fig.8. and its characteristics are listed in the table.V.From the data listed in the Table.V,it is understood that PIDN control loop gives better tradeoff between stability and dynamic response whereas PID control gives only better dynamic response but not better stability than PIDN.

4.2.2. Stability

Frequency response gives the information about the control loops. In a perfect control loop, the output voltage would remain locked to the reference voltage even if the load or input voltage changes. The frequency response indicates how a switching regulator will react under defined operating conditions across a range of frequencies. The frequency response is a dynamic model of the system showing how variations in the input voltage, the load and duty cycle affect the output voltage according to frequency. The frequency response Influences the reaction time, precision and stability of the system.

The frequency response of BBC in buck mode in analog domain is s shown in fig.9 can be determined from transfer function using bode plots which is basically a graph of magnitude and phase of the transfer function as a function of frequency, where magnitude is plotted in decibels and phase in degrees. These plots revel some key Information about the control loop's performance. The first point of interest is the crossover frequency (fc). Here ,BBC in buck mode is showing 360 Hz under PIDN control. This is the frequency at which the control loop gain is unity (0 dB) and is also referred to as the loop bandwidth. The second point of interest is the place at which the phase lag reaches 180^0 .In this case ,its 5.74 KHz under PIDN control The phase margin (PM) equals 180^0 minus the phase lag at fc. In this case its 122^0.The gain margin (GM) is the gain at a phase lag of 180^0.In this case its 40.8 dB under PIDN control. The system will be stable if the phase lag at fc is less than 180^0.Here in buck mode under PIDN control, its 120^0 therefore its stable. For most control loops, the engineers aim to achieve a PM greater than 45^0 and less than 180^0 .Typically, a phase margin of 45^0 provides good transient response with good damping. For buck or boost switching system the gain margin should be above 10dB.In this case,GM is 40.8 dB.The data which defines the stability of BBC in buck mode with PID and PIDN control loops is extracted from bode plots of analog domain which is as shown in fig.9 and is tabulated in the table .VI. Similarly the data which defines the stability of BBC in buck mode with PID and PIDN control loops is extracted from bode plots of digital domain which is as shown in fig.10 and is tabulated in the table .VII.

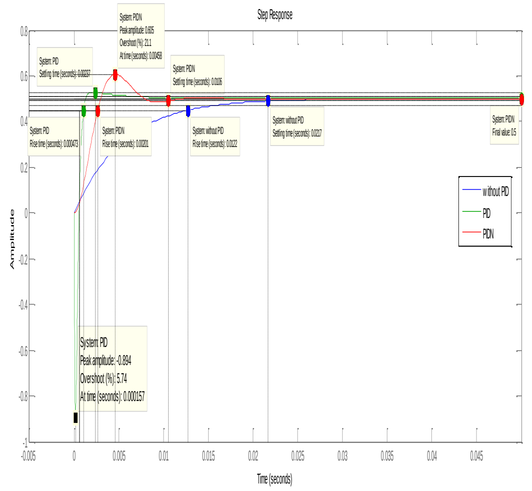

Fig.8. Step response of BBC in buck mode for 50% duty cycle.

TABLE. V. Step response of BBC with PID ,PIDN and without PID in buck mode.

BBC	Peak amplitude in volts	Overshoot	Rise Time in seconds	Settling time in seconds
Open loop	0.0%	0.0%	0.0122	0.0217
PID	-0.894	5.74	0.0000473	0.00237
PIDN	0.605	21.1	0.00201	0.0106

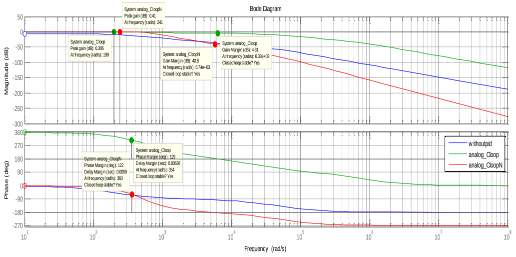

Fig.9. Analog domain- Frequency response of BBC with PID,PIDN and without PID control in buck mode.

TABLE VI. Comparison of stability analysis in analog domain of BBC in buck mode of operation.

System	PM (degrees)	GM (db)	ω_g (rad/sec)	ω_p (rad/sec)	Delay Margin (sec)	Stability state
Open loop	Inf	Inf	Inf	Inf	Inf	Stable with poor dynamic response
with PID control	129	4.81	6330	354	0.00636	Stable with good dynamic response
with PIDN control	122	40.8	5740	360	0.0059	Stable with better dynamic response

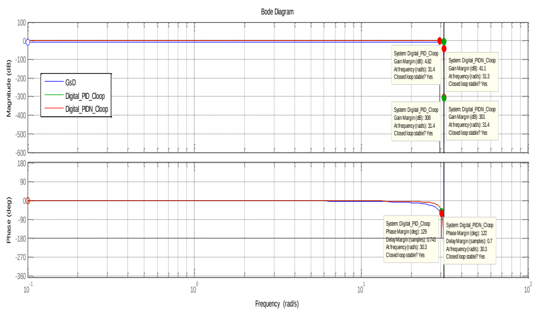

Fig.10. Digital domain- Frequency response of BBC with PID,PIDN and without PID control in buck mode.

TABLE VII. Comparison of stability analysis in digital domain of BBC in buck mode of operation

System	PM (degrees)	GM(db)	ω_g (rad/sec)	ω_p (rad/sec)	Delay Margin (samples)	Stability state
Open loop	Inf	Inf	Inf	Inf	Inf	Stable with poor dynamic response
with PID control	129	4.82 & 308	31.4	30.3	0.743	stable
with PIDN control	122	41.1 & 301	31.3 & 31.4	30.3	0.7	stable

From Table.VI and table VII, it is understood that the delay margin is more in digital control compare to analog control because of delay offered by ADC,control algorithm and DPWM and which can be overcome by predictive or deadbeat digital current control technique [12],where the current is sampled once per switching cycle. Another technique is based on a multiple sampling technique that can achieve a significant reduction of the DPWM delay by executing the control algorithm at a frequency of at least twice the converter frequency [13]. Analog and Digital control loops offers delay in closed loop control of power converters either it can be current mode control , voltage mode control or both . Analog control loops offers minimum delay compare to digital control loops where the delays are offered by ADC block, computation of algorithm and DPWM..Such delays results in reduction of maximum achievable closed-loop control bandwidth [8]-[10]. The closed loop control bandwidth is very important design parameter in power control system used in hybrid renewable energy harvesting system as it determines how fast the power conditioning unit will respond during transients [5]-[7]. However analog controllers hinders practical realization of the advanced control schemes , environmental conditions highly susceptible to the aging effects and limits the possibilities of implementing the operational dead-zone avoidance algorithms.[1]-[4]. The digital implementation in modern DSP controllers offers simpler implementation of complex control algorithms, higher robustness to noise and higher flexibility to changes in input/output parameters of the systems [11].

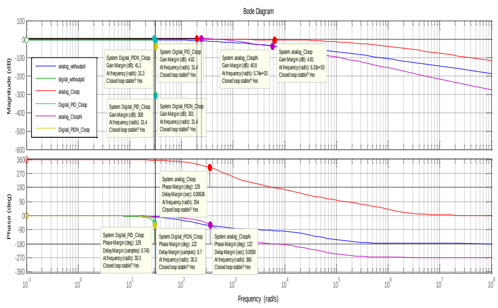

Fig.11. Mixed domain - Frequency response of BBC in buck mode in open loop, closed loop with PID and PIDN

V. CONCLUSION

Control loops behaviors of BDC with constant power loads are characterized in analog and digital control technology using PID and PIDN control logics in simulation using matlab code. Comparative analysis of dynamic response and stability in open loop and closed loop control with PID and PIDN also revealed. PIDN control logic gives better tradeoff between dynamic response and stability of the system in both analog and digital control. Further control loop transfer function models can be realized on hardware platforms of analog technology as well as digital technologies like microcontrollers, DSPs and FPGA for stability and dynamic characteristics that results in good reliability of the system

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