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| RESEARCH ARTICLE

Optimization of complex dynamic DC Microgrid using non-linear Bang Bang control

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| ABSTRACT

DC microgrids are gaining importance in various power electronics applications because of their efficiency in integrating diverse distributed energy sources. However, designing such complex systems is a great challenge, especially when it comes to high efficiency with minimum power losses and signal distortions that would affect the quality of the output. These systems are inherently dynamic and nonlinear, requiring robust control strategies to accomplish stability and quick dynamics under changing load and operating conditions. Linear and nonlinear control techniques can adopt solutions to the present challenges. For a proposed system, a nonlinear bang- bang control strategy is adopted for DC microgrid performance enhancement. It provides fast operation and enhances the system's overall stability. The performance of the system has been rigorously evaluated and analyzed under different scenarios to validate its effectiveness and reliability. Results are stated in favor of the feasibility and efficiency of the proposed control in the maintenance of the desired output characteristics.

| KEYWORDS

DC Microgrid, Power Electronics, Non-linear Control, Bang-Bang Control, System Optimization, Signal Distortion, Dynamic Systems, Control Techniques, System Stability, Efficiency Enhancement

| ARTICLE INFORMATION

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1. Introduction

Dynamic DC microgrids are real-life complex system which has stability as well as undershooting and overshooting issues [1]. The number of sources and loads are connected to the same microgrid bus and the microgrid should provide proper synchronization between all these circuitries. So, to ensure proper operation with less loss and efficient output from the microgrid, various control techniques were developed including Linear as well as Non-linear control techniques. Considering the given system in which 2 boost converters are connected to the grid as the source and one passive load is connected which comprises of Capacitor and Resistor combination will limit the flow of current in the Load circuit depending upon switch (s) condition.

DC-DC boost converters are widely used in real-life electronic applications. The basic principle of working is to step up the DC source voltage and to give an output voltage that is higher than the source input voltage. Here for a given system, boost converter circuits are comprised of 2 switches, a resistor, and one passive element which is a capacitor for energy storage purposes. Due to passive storage elements some of the power will get conserved inside the circuit ($P = VI,$) thus output current will be less than the source input current for the boost converter. In the provided system schematic, Source 1 and Source 2 are identical-looking two different boost converters with different parameter values. Boost converters are non-linear and like a DC microgrid and it also have stability and overshoot undershoot problems.

Passive load connected to the bus, which is a combination of capacitor and resistor and is fed by a combination of output currents of two different boost converter sources via the same bus. Resistance seen by this load circuit from the bus side will be dependent upon the switch (s) position at that moment. Thus, current flowing in the load circuit will be limited by a combination of two resistors. DC microgrid is a distributed energy resource which is a group of sources and loads coupled together on a single bus, which provides sufficient and continuous energy to fulfill system requirements.

Now to synchronize Sources, Load, and Bus all together efficiently with minimum overshoots and fast stable response, different control techniques are used. In synchronization with a complete system to achieve desired performance, non-linear control techniques such as bang bang switch control can be used. It optimizes the system and makes the system more stable in less time without compromising on efficiency part. Designing of the bang bang control is achieved by providing state equation models such as Switched mode equations which are constructed depending upon switching position inside the system for different time instants and Average mode model which are constructed from the switched mode model just by replacing the switch (q) in terms of (D) for whole system equations. These models provide steady-state final values for a given system. These boundary condition values are used to find the minimization time for the system. So that we can generate bang bang control in such a way that it will minimize the system as quickly as possible and will remove the vibrations from the output of the system.

Real-life complex microgrid response under bang-bang control can be analyzed with the help of a Pulse Width Modulated (PWM) signal which is synchronized with bang-bang control. PWM controls the amplitude of the signal. and thereby controls power. It is important to observe these systems because, in a real-life complex system, the response of the systems will be never a steady state straight-line output.

Thus, the effect of PWM on system performance under a steady state can be analyzed under bang- bang control.

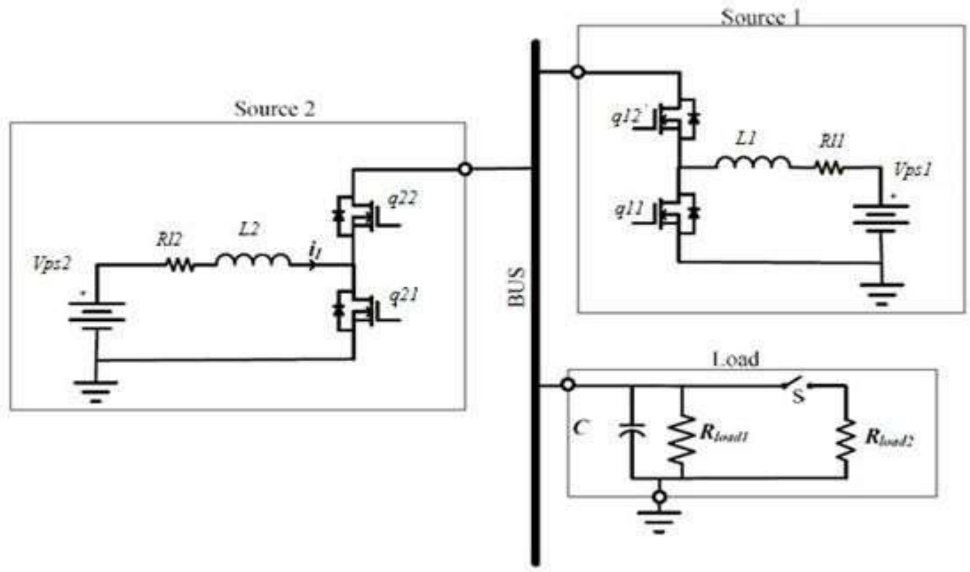


Figure 1. *DC microgrid along with 2 different source converters and passive load Given parameter values for the system are as follow.*

Source 1	L1 = 2m*H*	$R_{l1} = 125\ m\Omega$	$V_{ps1} = 200V_{dc}$
Source 2	$L_2 = 10mH$	$R_{l2} = 25\ m\Omega$	$V_{ps2} = 225V_{dc}$
Load	C = 1000 μF	$R_{load1} = 32\ \Omega$	$R_{load2} = 53\Omega$

To begin with the dynamics of a system and its solution that would be required for optimal control, differential equations may be constructed for the sources and load along with the DC microgrid.[4]

II. DC MICROGRID DIFFERENTIAL EQUATIONS

1. *Switched mode model*

- **For source 1,**

q11 = 1 (ON state)

Initially when q11 is ON, the inductor (L1) stores energy as inductor current i_{l1} flows through it and source 1 is disconnected from the DC microgrid bus as q12 is in the off state. Thus, the voltage across the inductor will be,

$$L1\frac{di_{L1}}{dt} = V_{ps1} - i_{L1}.R_{l1} \quad \text{.............. (1)}$$

q12 = 1 (ON state)

When q12 is ON, source 1 is connected to the DC microgrid through the inductor, and the boost converter will feed the boosted voltage and then the source input voltage to the microgrid. Thus, Voltage across the inductor will be,

$$L1\ \frac{di_{L1}}{dt} = V_{ps1} - i_{L1}.R_{l1} - V_{cbus} \quad \text{.............. (2)}$$

- For source 2 q21 = 1 (ON state)

Initially when q21 is ON, the inductor (L2) stores energy, and source 1 is disconnected from DC microgrid bus as q22 is in the off state. The inductor voltage will be,

$$L2\frac{di_{L2}}{dt} = V_{ps2} - i_{L2}.R_{l2} \quad \text{.............. (3)}$$

q22 = 1 (ON state)

When q22 is turned on, source 2 will be connected to DC microgrid with a boosted voltage that is greater than the source input voltage, the inductor voltage will be,

$$L2\frac{di_{L2}}{dt} = V_{ps2} - i_{L2}.R_{l2} - V_{cbus} \quad \text{.............. (4)}$$

- For load,

s = 0 (OFF state)

Current flowing through the DC microgrid ($i_{L1} + i_{L2}$) will charge the capacitor, thus voltage appearing across R_{load1}will be the same as the capacitor voltage because it is connected in parallel with the capacitor.

$$C\frac{dV_{cbus}}{dt} = \frac{V_{cbus}}{R_{load1}} \quad \text{.............. (5)}$$

s = 1 (ON state)

When the switch (s) on the load side are closed $R_{load1}$and R_{load2}will be connected in parallel, according to KCL current will be limited

by $R_{load1}\|\ R_{load2}$ that is equal to R_{eq}.

$$C\frac{dV_{cbus}}{dt} = i_{L1} + i_{L2} - \frac{V_{cbus}}{R_{eq}} \quad \text{.............. (6)}$$

So, we can substitute $R_{eq} = R_{load1}$ for s=0 in the above equation even when switch s is open for simulation purpose.

Now comparing all the equations derived from (1) to (6), it is possible to construct common switching model for individual topology to eliminate complementary switching state. Thus state model equations for Source 1, Source 2 and Load will be

$$L1\frac{di_{L1}}{dt} = V_{ps1} - i_{L1}.R_{l1} - (1 - q_{11})V_{cbus} \quad \text{.............. (7)}$$

$$L2\frac{di_{L2}}{dt} = V_{ps2} - i_{L2}.R_{l2} - (1 - q_{21})V_{cbus} \quad \text{.............. (8)}$$

$$C\frac{dV_{cbus}}{dt} = (1 - q_{11})i_{L1} + (1 - q_{21})i_{L2} - \frac{V_{cbus}}{R_{eq}} \quad \text{.............. (9)}$$

1. *Average mode model*

Once switching model equations are constructed, average mode model equations can be generated by simply replacing "q" (switch) with "D" (duty cycle).

Thus, we can reconstruct equations (7), (8), (9) by replacing q_{11} and q_{21} by D_1 and respectively.

$$L1\frac{di_{L1}}{dt} = V_{ps1} - i_{L1}.R_{l1} - (1 - D_1)V_{cbus} \quad \text{.............. (10)}$$

$$L2\frac{di_{L2}}{dt} = V_{ps2} - i_{L2}.R_{l2} - (1 - D_2)V_{cbus} \quad \text{.............. (11)}$$

$$C\frac{dV_{cbus}}{dt} = (1 - D_1)i_{L1} + (1 - D_2)i_{L2} - (1 - D_1)\frac{V_{cbus}}{R_{eq}} \quad \text{.............. (12)}$$

Here equations (10), (11), and (12) are average mode model equations for the entire system.

2. *Steady state model*

Assuming the system to be operated in a steady state, the rate of change of voltage across the capacitor ($\frac{dV_{cbus}}{dt}$) and rate of change current across the inductor ($\frac{di_{L1}}{dt}$) will be equal to zero, thus we can substitute $\frac{di_{L1}}{dt} = 0, \frac{di_{L2}}{dt} = 0, \frac{dV_{cbus}}{dt}$ = 0 in equation (10), (11), (12) respectively.

*Note: For the given system, it is assumed that source 1 output current i_{L1} is equal to source 2 output current i_{L2}. Also, the bus voltage is assumed to be 575 V to evaluate and analyze system response.

Thus, steady-state equation for the given system (Source 1, Source 2, Load connected to Microgrid) will be

$$0 = V_{ps1} - i_{L1}.R_{l1} - (1 - D_1)V_{cbus} \quad \text{...............(13)}$$

$$0 = V_{ps2} - i_{L2}.R_{l2} - (1 - D_2)V_{cbus} \quad \text{...............(14)}$$

$$0 = (1 - D_1)i_{L1} + (1 - D_2)i_{L2} - \frac{V_{cbus}}{R_{eq}} \quad \text{...............(15)}$$

Respectively,

These equations are solved by rearranging the equations (13),(14) and (15) and so can be written in terms of i_L and D. We can Solve these equations for i) s = 0 and ii) s = 1.

For s = 0, and rearranging the equations in terms of i_L and D we get,

$$i_{L1} \to \frac{\mathrm{R}_{load1}V_{ps1} - \sqrt{\mathrm{R}_{load1}{}^2 V_{ps1}{}^2 - 2R_{l1}\mathrm{R}_{load1}V_{cbus}{}^2}}{2R_{l1}\mathrm{R}_{load1}}$$

$$i_{L2} \to \frac{\mathrm{R}_{load1}V_{ps2} - \sqrt{\mathrm{R}_{load1}{}^2 V_{ps2}{}^2 - 2R_{l2}\mathrm{R}_{load1}V_{cbus}{}^2}}{2R_{l2}\mathrm{R}_{load1}}$$

$$\mathrm{D1} \to \frac{-V_{ps1} + 2V_{cbus} - \frac{\sqrt{\mathrm{R}_{load1}(\mathrm{R}_{load1}V_{ps1}{}^2 - 2R_{l1}V_{cbus}{}^2)}}{\mathrm{R}_{load1}}}{2V_{cbus}}$$

$$\mathrm{D2} \to \frac{-V_{ps2} + 2V_{cbus} - \frac{\sqrt{\mathrm{R}_{load1}(\mathrm{R}_{load1}V_{ps2}{}^2 - 2\mathrm{Rl2}V_{cbus}{}^2)}}{\mathrm{R}_{load1}}}{2V_{cbus}}$$

Substituting given parameter values in the above equations, the equation is reduced and gives numerical values for $i_{L1}, i_{L2}, D1, D2$ for s = 0. Alternative way to avoid analytical mathematical calculations these equations can be solved in Mathematica.

In Mathematica, all the state equations are defined as a function "*f*", and to find steady-state values from defined functions, all these functions are equated to zero and can be solved for required steady-state parameters with proper substitution of given parameters using "*solve*" command which solves these expressions for variables of that system. The proposed system has 4 unknown variables which are solved using this command.

As a quadratic function, set of results generated is,

$$\{\boldsymbol{i_{L1}} \to 26.26110670330138, \boldsymbol{i_{L2}} \to 23.01894408743351, \mathrm{D1} \to 0.6578828492833264, \mathrm{D2} \to 0.6096964758298885$$
}

$$\{\boldsymbol{i_{L1}} \to 1573.7388932966987, \boldsymbol{i_{L2}} \to 23.01894408743351, \mathrm{D1} \to 0.994291063760152, \mathrm{D2} \to 0.6096964758298885\}$$

$$\{\boldsymbol{i_{L1}} \to 26.26110670330138, \boldsymbol{i_{L2}} \to 8976.981055912567, \mathrm{D1} \to 0.6578828492833264, \mathrm{D2} \to 0.9989991763440246\}$$

$$\{\boldsymbol{i_{L1}} \to 1573.7388932966987, \boldsymbol{i_{L2}} \to 8976.981055912567, \mathrm{D1} \to 0.994291063760152, \mathrm{D2} \to 0.9989991763440246\}$$

$i_{L1}(Amp)$	$i_{L2}(Amp)$	D_1	D_2
26.26110670330138	23.01894408743351	0.6578828492833264	0.6096964758298885

Table (1)

Similarly, the same method can solve these equations for s = 1. (Only R_{load1} is replaced by R_{eq}) Acceptable results for s =1 is,

$i_{L1}(Amp)$	$i_{L2}(Amp)$	D_1	D_2
42.557563367802324	36.97465567843742	0.6614255572538701	0.6103032458990625

Table (2)

These values can be used for optimization of the system as per system requirements and can be used as boundary conditions for optimal control designing

BANG BANG CONTROL

Boost converter topologies have the same problem as other dynamic systems, it is a non-linear system and has some stability issues, overshooting and undershooting while feeding some passive loads and sensitive loads. It is desired to minimize one of these aspects. It is possible to minimize these aspects using linear control techniques but the major drawback for these linear control techniques is that they operate on a very small linear part of non-linear system response, thus for optimal control (to minimize settling time) and to reduce down the vibrations of the whole system we can use non-linear control techniques.

For optimization of a given system, Bang Bang control, a non-linear control technique, is used to drive the system from an initial state to a final state in minimum time. To find switching time in order to obtain the smallest transient time Bang Bang control formulations and boundary constraints are used. In this control technique, duty cycle changes such that system traces fastest trajectory path to rech to steady state as soon as possible.

Considering state equations having linear control to obtain general bang bang control model,[2][3]

$$\dot{x} = f[x(t), t] + G[x(t), t]u(t), \qquad x(t_0) = x_0 \quad \text{...............(16)}$$

$$a_i \le u_i \le b_i, \qquad \forall i \quad \text{...............(17)}$$

Hamiltonian (H) to be obtained must be linear with input control i.e u(t) thus objective function is assumed such that it contains only linear control variables.

Thus, objective function with linear control variables is designed to minimize the time such that,

$$J(x) = \Theta[x(t_f), t_f] + \int_{t_0}^{t_f} \{\phi[x(t_f), t_f] + u(t)h[x(t_f), t_f]\}dt \quad \text{...............(18)}$$

And the Hamiltonian will be,

$$H = \phi[x(t_f), t_f] + u(t)h[x(t_f), t_f] + \lambda(t)\{f[x(t_f), t_f] + g[x(t_f), t_f]u(t)\} \quad \text{............(19)}$$

For the minimum principle the solution will be,

$$\partial_{u(t)}H = 0 = h[x(t_f), t_f] + \lambda(t)g[x(t_f), t_f] \quad \text{............(20)}$$

The solution obtained in equation (20) is not a function of control input u(t), Minimization of Hamiltonian with respect to u(t) is possible and it requires,

$$u_i = \begin{cases} a_i & if\ h[x(t_f), t_f] + \lambda(t) g[x(t_f), t_f] > 0 \\ b_i & if\ h[x(t_f), t_f] + \lambda(t) g[x(t_f), t_f] < 0 \end{cases}$$ ....(21) Finding co-state solution with boundary constraints will be,

$$\partial_{x(t)} H + \dot{\lambda}(t) = 0$$ ....(22)

$$\{\partial_{x(t)} \Theta[x(t_f), t_f] - \lambda\}\Big|_{t_0}^{t_f} = 0$$ ....(23)

Using external bang bang control input u(t) will switch between its upper and lower limits for maximum n-1 times where n is the number of states or we can say dimension of x.

Now, to start with the external bang-bang control, we use all the steady state values that we obtained in Table (1) as a final steady-state value for "s"= 0 and we start with initial values for all these states equal to zero. So once the system reaches its final steady-state values "s" can be turned on ("s" = 1) and now the system will take the previous final steady-state values of "s" = 0 as an initial value and will stabilize the system for its final steady-state values mentioned in Table (2) in minimum time.

Application of the objective function for DC microgrid system that we are using, the following function can be implemented.

$$J = (i_{Lf1} - i_L)^2 + (i_{Lf1} - i_L)^2 + (v_{cf} - V_{cbus})^2 + \int_0^{t_f} 1\, dt$$ ....(24)

For the provided nonlinear system, each component of the control vector u(t) is restricted to a finite bounded interval. Thus, Hamiltonian is generated which is in linear fashion with control vector u(t) and is minimized using equations (19) and (21). Co-state solutions can be found using
(22). To solve this problem, we must know t_f, however, t_f is unknown and we cannot solve this directly as it is a free-time problem, so it is advisable to use time scaling such that,

t = t_fτ

By taking τ in the range from 0 to 1 and t_f as a scaling factor, t can be calculated for any range. After these changes, a time differential will be added such that dt = $t_f d$τ. It will modify the state equations that we obtained in the previous part; Modification will be simply multiplication by t_f.

Now the modified state equations will be,

$$L1 \frac{di_{L1}}{dt} = t_f(V_{ps1} - i_{L1}.R_{l1} - (1 - q_{11})V_{cbus})$$ ....(25)

$$L2 \frac{di_{L2}}{dt} = t_f(V_{ps2} - i_{L2}.R_{l2} - (1 - q_{21})V_{cbus})$$ ....(26)

$$C \frac{dV_{cbus}}{dt} = t_f\left((1 - q_{11})i_{L1} + (1 - q_{21})i_{L2} - \frac{V_{cbus}}{R_{eqvt}}\right)$$ ....(27)

The new objective function can be defined as follows,

$$J = (i_{Lf1} - i_L)^2 + (i_{Lf1} - i_L)^2 + (v_{cf} - V_{cbus})^2 + \frac{1}{2} t_f^2$$ ....(28)

The last term in equation (28) is negligible and can be ignored. A system model can be used to design the system with proper evaluation of all the variables such that the system model should be globally balanced. All the variables, state equations, objective functions, and switching conditions are included in the system modeler. By substituting initial conditions and final steady-state values obtained from the average mode model, this model is evaluated and its output current and bus voltage response for different switching conditions are observed. This model is then extracted in Mathematica using "*import*" and simulated using the "WSMsimulate" command to find out $t_{s1}t_{s2}$ and t_f. To do so, final steady-state values for respective states are provided to the system, and the objective function is minimized to find $t_{s1}t_{s2}$ and $t_f$which are unknown parameters with the loop time constraints. To find values of these unknown parameters, the command "*Reap[FindArgMin]*" is used in Mathematica which in turn gives return values for minimization of objective function that is restricted to a constraint.

The Efficiency of Bang-Bang Control in DC Microgrids

- **Benefits**

Parameter	**Traditional Control**	**Bang-Bang Control in Your System**
Settling Time	Long (due to linear zone)	Minimum possible (time-optimal)
Overshoot	Possible	Drastically reduced
Control Effort	Spread over time	Instant switch, minimal energy loss
Load Handling	Struggles with sensitive loads	Handles sensitive/passive loads better
Computational Load	Moderate	High (solved via Mathematica optimization)

Advantages of Bang-Bang Control

The Bang-Bang controller has a clear advantage when managing boost converters' nonlinear dynamics within your DC microgrid. Linear controllers like PID or state feedback work over small operating ranges and hence would fail this nonlinear task. Bang-Bang works through the whole nonlinear system by modulating control inputs between limits of values alternately, forcing the system on the fastest path toward the steady state.

For some reasons, this method is beneficial for your configuration:

[1] **Time-Optimal Performance:** It allows a minimal transient response time. Thus, it minimizes the time when voltage and current deviate from their regulated state and returns them quickly, which is of utmost importance, especially for the load protection of sensitive electronics.

[2] **Better Transient Handling:** Since Bang-Bang control firmly regulates the switching between states, it alleviates overshoots, undershoots, and voltage ripple, which could otherwise destabilize the system or destroy passive components.

[3] **Use of Minimum Energy:** The shorter the amount of time taken by the system to reach the desired operating point, the less energy is lost during this transition period. Thus, this improves the overall efficiency of power provided from Source 1 and Source 2 to the DC bus.

[4] **Smooth Compatibility with Simulation Tools:** Your optimization work in Mathematica (e.g., WSMsimulate, FindArgMin) is perfectly coupled with Bang-Bang control because it allows for accurate tuning of switching times as well as the minimization of the objective function.

[5] **Scalability and Simple:** The binary state controller input has been simplified for deployment in hardware. It lends itself easily to scaling over a great many converter stages without increasing any algorithmic complexity.

- *Alternative Control Technologies: Comparative Analysis with Bang-Bang Control*

Boost converters, like almost all power electronic systems, pose considerable control challenges owing to the noticeably nonlinear character of their dynamics. While Bang-Bang control delivers the fastest possible response, it is worthwhile to examine other control strategies that are also commonly used in such systems. The present section will analyze these alternative technologies, comparing them to Bang-Bang controls in terms of their various advantages and disadvantages, as well as their practical applicability.

1. *PID Control (Proportional-Integral-Derivative)*

1) Overview:

The PID controller is the most widely used control method in industry and automation applications. PID works based on the error, which is the difference between the measured value of a process variable and the desired setpoint. The control input is adjusted upon three terms: proportional, integral, and derivative.

2) Advantages:

- Simple implementation and tuning.
- A stable and predictable response is presented by linear systems.
- Relatively inexpensive with low computational requirements.

3) Limitations:

- Its performance is greatly affected by nonlinearity or time-varying factors, especially in the case of boost converters.
- May lead to overshooting and extended settling times in response.
- Not necessarily the best choice for systems requiring fast time-optimal control.
- Poor adaptability in a highly dynamic environment.

Comparison to Bang-Bang: PID imparts smoother control inputs, while Bang-Bang control is better suited for performance where time optimality is of utmost concern, especially in situations where convergence with minimal delay is crucial.

B. Sliding Mode Control (SMC)

1) Overview:

An approach to nonlinear control that is robust enough to drive a system trajectory onto a given sliding surface and hold it on this surface in the presence of uncertainty.

2) Advantages:

- Robust to parameter variation and disturbance.
- Applicable for systems having uncertain dynamics.
- Retains performance in the presence of modeling inaccuracies.

3) Constraints:

- Is suffering from the chattering effect due to high-frequency switching exerting wear and tear on its components.
- Design and tuning of the sliding surface are complex.
- More computation-intensive than Bang-Bang control.

Comparison: Both SMC and Bang-Bang have high-frequency switching, while Bang-Bang methods are much simpler. SMC provides tighter control in conditions of uncertainty.

C. Model Predictive Control (MPC)

In brief:

MPC imbues a measurement with the optimality of its control input by mathematically predicting the future behavior of the system model for a defined time horizon.

1) Pros:

- Effectively handles multiple variables with a constraint structure.
- Superior dynamic performance both at steady-state and during transients.
- Versatile and suitable for predictive energy management.

2) Cons:

- High computation burden and thus unsuitable for implementing real-time algorithms in embedded systems.
- Requires very accurate system modeling and parameter identification.
- Not intuitive compared to Bang-Bang control.

Comparison with Bang-Bang: Complex MPC systems with constraints; Bang-Bang is the straightforward tool for the times when fast response and ease of implementation are the overriding concerns.

D. Hysteresis Control

1) Overview:

It is a bang-bang-like method that switches the control input on errors exceeding a given band or threshold.

2) Advantages:

- A simple and very responsive control method.
- Does not require any system model.
- Good for current control in converters.

3) Limitations:

- The switching frequency varies, creating difficulties for filter design and EMI considerations.
- Less applicable for tight voltage regulation.

Comparison with Bang-Bang: Both use no deliberating switching; Bang-Bang is intended for minimum time control, while hysteresis control is concerned about bounded error with less emphasis on timing.

- **RESULTS**

Optimization of DC Microgrid system using bang bang control can be analyzed for 2 switching conditions i.e., for s = 0 and s = 1. In this section simulation graphs for desired system parameters are listed in following table.

For s = o **For s =1**

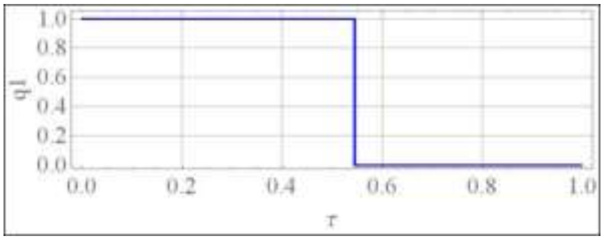
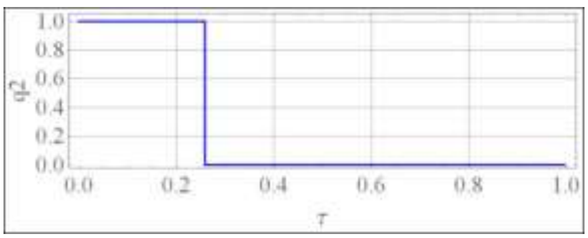


Figure 1:

Figure 2: Simulation result for switching time t_{s1}

Figure 3: Simulation result for switching time t_{s1}



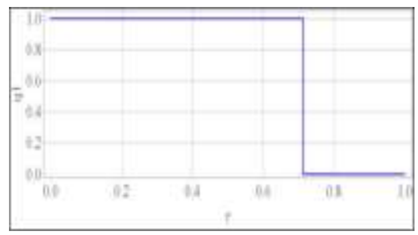


Figure 4: Simulation result for switching time t_{s1}

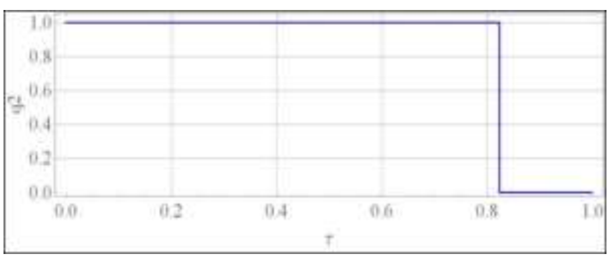
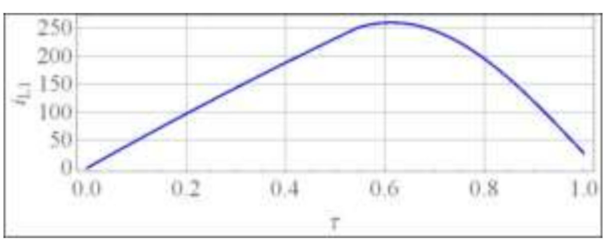


Figure 5: Simulation result for switching time t_{s2}

Figure 6: Simulation result for switching time t_{s2}



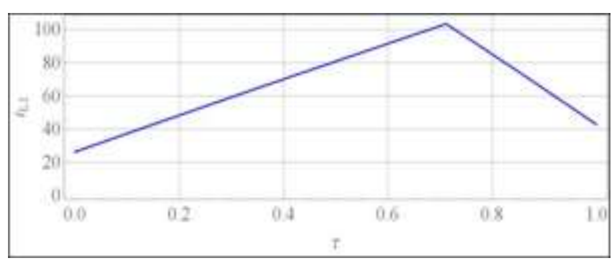
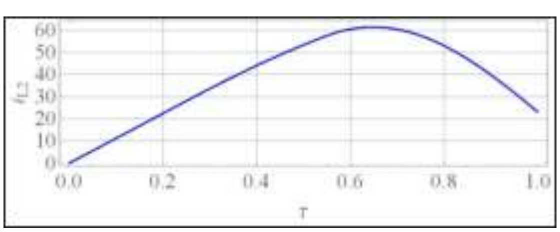


Figure 7: Simulation result for i_{L1}

Figure 8: Simulation result for i_{L1}



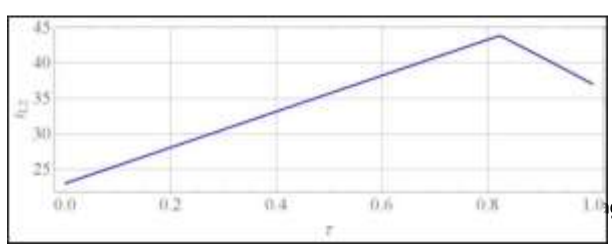
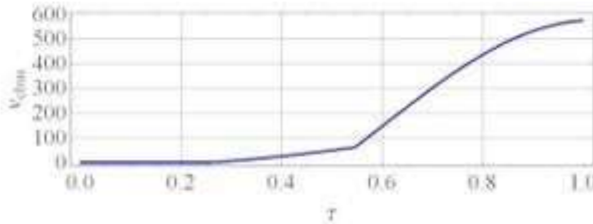


Figure 9: Simulation result for i_{L2}

Figure 10: Simulation result for i_{L2}



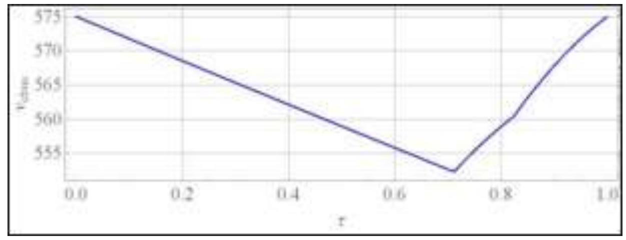


Figure 11: For real time system with t = $t_f\tau$

Figure 12: For real time system with t = $t_f\tau$

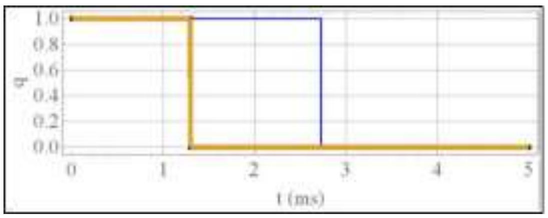
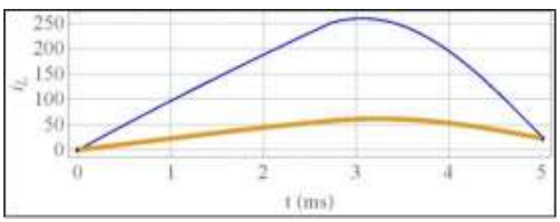


Figure 13: Simulation result for q

Figure 14: Simulation result for q



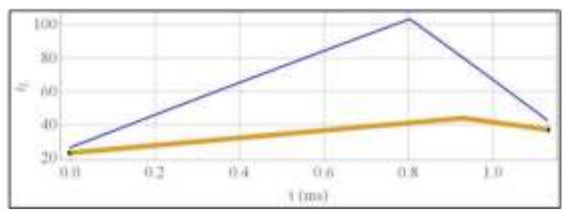
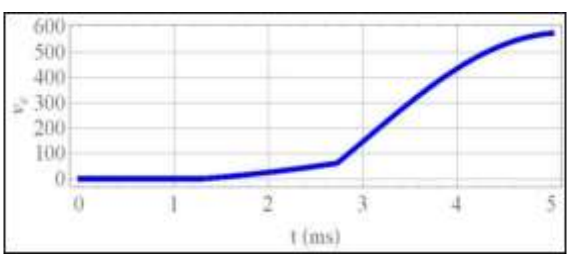


Figure 15: Simulation result for i_L

Figure 16: Simulation result for i_{L2}.



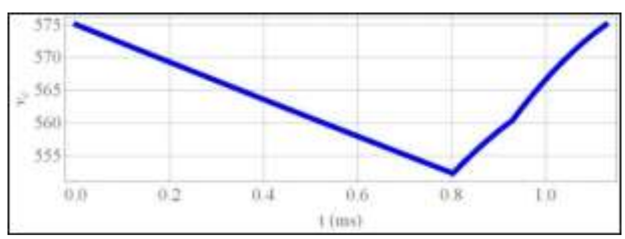


Figure 17: Simulation result for v_c

4) Bang Bang control with PWM at 10kHz

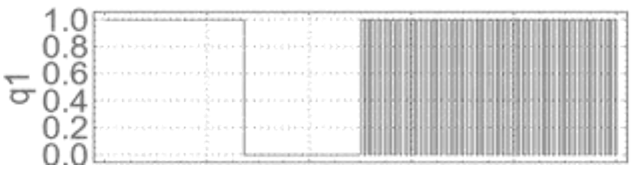


Figure 18: Simulation result for q1 with PWM

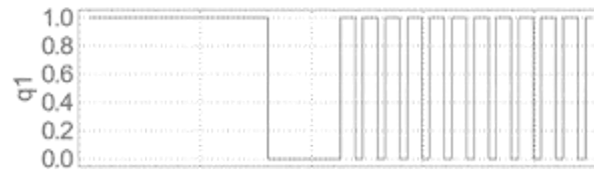


Figure 19: Simulation result for q1 with PWM

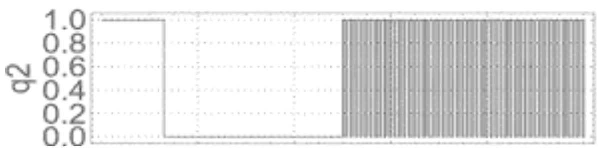


Figure 20: Simulation result for q2 with PWM

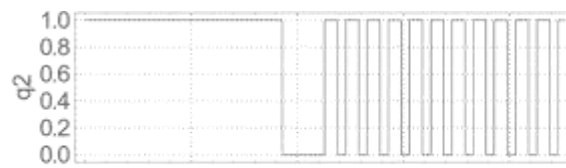


Figure 21: Simulation result for q2 with PWM

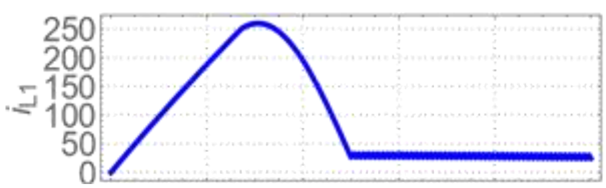


Figure 22: Simulation result for $i_{L1}$with PWM

Figure 23: Simulation result for $i_{L1}$with PWM

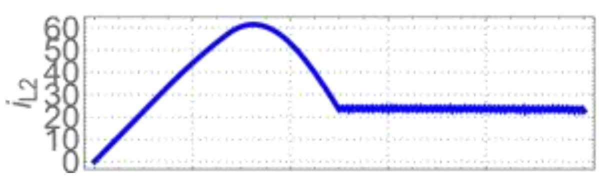


Figure 24: Simulation result for $i_{L2}$with PWM

Figure 25: Simulation result for $i_{L2}$with PWM

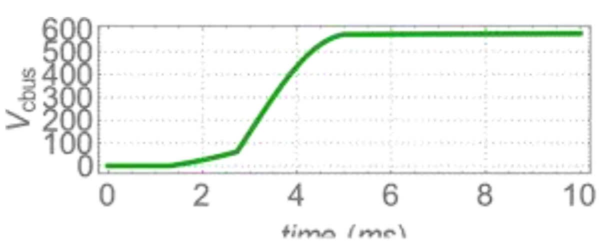


Figure 26: Simulation result for $V_{cbus}$with PWM

Figure 27: Simulation result for $V_{cbus}$with PWM

5) For s = 0,

Referring to figures 1 and 2, it can be seen that switching times for q1 and q2 are approximately

0.5 sec and 0.25 sec. In the bang-bang control technique, calculated final steady-state values are used as end-time boundary constraints, and initial values are set to zero. The system is required to optimize in minimum time, therefore bang bang switch will minimize the settling time with 2 switching for the total system as the system has 3 states, and bang bang switch shifts between upper and lower bound at most n-1 times, where n is the dimension of states. Using "*Reap*" and "FindArgMean" functions in mathematical switching time t_{s1} = 0.5449324790615369 sec and t_{s2} = 0.2587384759314775 sec and minimum time t_f =0 .005003226633321484 sec. Using boundary conditions and final steady-state values for i_{L1} , i_{L2}, V_{cbus} system achieves steady state, from Figure 3,4 and 5 it can be seen that i_{L1} is approximately 26 A, $i_{L2}$is approximately 23A, V_{cbus} is approximately 575V with scaled time τ at the boundary conditions. Thus system starts with 0 initial values and by the end it has i_{L1}=26.261A, i_{L2} = 23.0189A and V_{cbus} = 575 v. These obtained values in Table(1) matches with graphical values. i_{L1}, i_{L2} has overshooting issues as well as V_{cbus} has undershooting issue which are being controlled and compensated by bang bang swiching control.

In a real time system, it is desired to observe response over long period of time thus for such system in which bang bang control is implemented to observe the response by setting time t = t_f τ. Thus τ which takes values from 0 to 1, now can be operated over required range of time because of multiplication by t_f. Referring figure 5, which gives result for both switching with their respective switching time i.e t_{s1} for q1 and $t_{s2}$for q2. We can write from the result and conclusion can be made such as,

$$q_1(t) = \begin{cases} 1, & if\ t < 0.5449324790615369\ sec \\ 0, & if\ t \geq 0.0.5449324790615369\ sec \end{cases}$$

$$q_2(t) = \begin{cases} 1, & if\ t < 0.2587384759314775\ sec \\ 0, & if\ t \geq 0.2587384759314775\ sec \end{cases}$$

i_{L1} has the maximum overshooting issue, as it starts from 0 and goes up to peak value of approximately 250 A, this overshoot is comparatively greater than i_{L2} which has peak value of overshoot at 60 A approximately, also it is observed that this overshooting problem is compensated by implementation of bang bang control in such a way that i_{L1}, i_{L2} reaches at their steady-state values in a same time. In between the switching, V_{cbus} changes twice which can be seen in figure 6, 9, and 13, and gradually increases as load current decreases. It gains its final steady state as soon as load currents reach to final steady state. So bang bang switching provides exact synchronization between the system parameters with minimum errors in system output.

A real-life complex system that has some noise and ripples in the output has an impact on system stability and efficiency. So, to minimize these effects using bang bang control, the PWM signal with 10Khz is synchronized in such a way that it modulates the system output signal after bang bang control, which in turn modulates the steady-state voltage and current signals. PWM uses switching for modulation of signal which causes the transition effects and are visualized in figure 11, 12, and 13. Visual analysis of these figures can conclude that the system reaches its final steady-state values within 5ms, i.e. so this is the best optimization provided by the bang bang switch control for this system.

Obtained values for t_{s1}, t_{s2}, t_f are,

t_{s1} = 0.5449324790615369 sec

t_{s2} = 0.2587384759314775 sec

t_f= 0.005003226633321484 sec

For s = 1, ($R_{load1} \| R_{load2}$)

Referring to Figures 14 to 26, it is observed that q1 and q2 are switching from 1 to 0 at 0.75sec and 0.85 sec respectively.

So for switching,

$$q_1(t) = \begin{cases} 1, & if\ t < 0.7485408896848906sec \\ 0, & if\ t \geq 0.7485408896848906\ sec \end{cases}$$

$$q_2(t) = \begin{cases} 1, & if\ t < 0.8475798913011647\ sec \\ 0, & if\ t \geq 0.8475798913011647\ sec \end{cases}$$

As soon as q1 and q2 makes transition from 1 to 0, output currents i_{L1} and i_{L2} tries to minimize the overshooting and reaches the steady state values which are comparable and matched with the obtained values in Table (2). Also V_{cbus} which starts decreasing initially and again rises as output currents decreases after switching. When switch (s) is closed at t=1sec system loaded its previous final state steady state values as an initial values and adjusted the control such that it will again minimize the effects of switching. From figures 24,25 and 26 time required for control mechanism to settle down the system is approximately 1.4ms where as we solved and obtained this settling time $t_f = 1.4ms$ as well.

For s = 1, now steady state values for $i_{L1} = 42.5576\ \text{A}, i_{L2} = 36.9747\ \text{A}, V_{cbus} = 575V$. Comparing these values with the

previous state values, It is depicted that there is an increase in inductor current for both sources. As a stable distributed DC microgrid system, which optimizes the system performance, will fulfill the internal needs of load when s = 1, the current limiting load resistor is reduced to equivalent resistance thus current for s= 1 is greater than those current values we obtained for s = 0.

Initially system took a little longer time to settle down but once it settled down in its steady state for (s = 0), further switching actions (s = 1) and their effects are minimized in a much smaller settling time and can be observed by comparing the results obtained,

For s = 0, $t_f = 0.005003226633321484\ sec$ For s =1, t_f = 0.0014148013222513344 sec.

II. CONCLUSION

DC microgrid with bang bang switch control was designed to optimize the system performance. With the help of differential average mode model of the provided system, initially calculation of steady state values for i_{L1}, i_{L2}, D1 and D2 was done individually for two different switch conditions. Then using system modler, nonlinear bang bang control technique was implemented for the given system with properly substituting calculated initial values and final steady state values for s = 0 and s = 1. From the simulation results it was justified that bang bang switch control technique was successfully implemented and it forced system to become stable in minimum time t_f. Dynamic DC microgrid response for i_{L1}, i_{L2}, V_{cbus} achieved their final steady state values which exactly matches with the calculated values. It can be proved by comparing the values obtained from Figure 4, 5, 6

in results with Table (1) and values obtained from figure 17, 18, 19 in results with table(2). Few assumptions were made such as inductor output currents which are output currents for both the sources were identical and bus voltage is assumed to be 575 V. Mismatching parameters for identical looking boost converter sources gave dynamic and unstable response when connected to DC microgrid, so implementation of nonlinear control was introduced for provided system to maintain the internal load demands. In this case, as mentioned optimization of the system was best controlled by bang bang switch. Reason behind using nonlinear control technique over linear control technique is range of operation. Using Linear control for nonlinear systems will restrict the range of operation and will control only a small linear part of nonlinear system. Provided system with 3 state (n) equations required 2 switching (n-1) stabilize the system in possible minimum time.

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