Grey wolf optimizer for the design optimization of a DC-DC boost converter

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Article Info

ABSTRACT

Design optimization of a DC-DC boost converters for minimizing overall operational losses is the problem under study. The optimum design contains selecting the best value of circuit inductance, capacitance, and switching frequency for the continuous conduction mode (CCM) operation. The design constraints selected are the current ripple content, ripple content of voltage, and bandwidth for operation in CCM. Grey wolf optimizer (GWO) algorithm is implemented for the boost DC-DC converter's optimal design. The comparative investigation of algorithms reveals that GWO outperforms other established optimization algorithms like the particle swarm optimization (PSO), moth flame optimization (MFO) algorithm, simulated annealing (SA) and firefly algorithm (FFA) in terms of convergence time, computational effort, and the minimized system losses while finding the most efficient design of the converter. Parametric study on statistical performance indicates that the GWO algorithm outperforms the rest of the optimization algorithms on comparing with previously reported results. The optimized results obtained in the current work provides and improved converter design with reduction in the power loss in the optimized design of the converter by over 15% from previously reported works.

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1. INTRODUCTION

An intriguing research challenge is the use of optimization algorithms in the design of power electronic converters [1]. A manual DC-DC converter design takes a lot of effort and money. This paved the way for the application of optimization algorithms for suitable design of a converter topology depending on end utility and to ease the computational time. Recent advances in the field of electronics have led to the improvement in the manufacturing of DC-DC converters. Significant design improvements in the energy storage elements have been reported with reduced size and lower associated losses. The improvements in the blocking voltage, transients stress withstand capability, and lower operational losses are also significant improvements with respect to device technologies involving power electronic switches. Despite these improvements, choosing the optimal sizing design parameters that give efficient operation under a given set of constraints is still a problem of interest [2].

Review of available literature indicates that the problem of optimal design parameter selection for converters differ in terms of selection of objective functions, the design constraints as well as methodologies implemented for finding the optimized solution. Research by Yousefzadeh *et al.* [3], have used graphical approach for solving the design optimization problem in the for best efficiency of monolithic DC-DC

converter and loss optimization for envelop tracking in radio frequency (RF) amplifiers. Graphical methods when employed suffer from the limitation of variables to be optimized. At the most two variables can be used simultaneously. As such they are not viable solution method for design optimization problems with multiple variables and constraints. Balachandran and Lee [4] present an optimization approach involving choice of design to optimize the total weight or total losses resulting in a cost effective design. Tradeoff between the choice of design parameters in terms of efficiency, weight, optimal power configuration are additional advantages of the proposed computer aided method. According to Kursun *et al.* [5], decision factors are included in the study of the monolithic DC-DC buck converter's optimization, which constitute of switching frequency, ripple in current, and voltage swing in the metal oxide semiconductor field effect transistor (MOSFET) driver circuit. Moreover, the solution to the problems of reduction of electromagnetic interference (EMI) and improvement of converter efficiency is also carried out in [6], [7]. According to Seeman and Sanders [8], lagrangian function used for the optimization while augmented Lagrangian method was used in [9] quadratic programming [10], Monte Carlo [11] are also applied for converter design optimization for end applications.

DC-DC converter design optimization with geometric programming (GP) in [12], [13] makes use of monomial and posynomial expressions for the solution to the optimization problem. In recent years many more approaches like the graph based techniques [14] and automatic selection of parameters based on machine learning [15]. Genetic algorithm [16], particle swarm optimization (PSO) [17], honey bee mating algorithm [18] simulated annealing (SA), and firefly algorithm (FFA) [19] also find its application in the optimization of converters. In majority of the cases, it is seen that the optimization approach involves one parameter. These parameters selected are also varying in nature from loss minimization, improvement in efficiency, ripple minimization, voltage swing minimization, optimization of the component weights, and EMI minimization. Alternate solution techniques employ division of the optimization problem into sequential stages where individual stages solve the problem involving one or two parameters only. This solution methodology has the drawback of not allowing the provision for selection of all the possible constraints for the design optimization process. Research by Saharia and Sarmah [19], chose a very limited range of the switching converter's duty ratio. Consequently, when using PSO to optimize a DC-DC buck converter, the search space for this parameter is significantly reduced.

To ensure attainment of global optima, this paper presents the optimized DC-DC boost converter operating at minimum operational loss using the grey wolf optimizer (GWO). The problem formulation philosophy indicating the state space modelling for optimal selection of design parameters for the boost converter in presented in section 2, along with the formulation of design optimization problem. Section 3 present a brief overview of the GWO algorithm used to make comparative analysis with previously reported results. Section 4 discusses results obtained and presents a comparative study of the GWO with other popular algorithms like the moth flame optimization (MFO) [20], PSO [21], SA [22], and FA [23]. The paper concludes in section 5.

2.   METHOD AND PROBLEM FORMULATION

A DC-DC converter's design optimization aims to reduce the overall power loss in the various stages of the switch operation MOSFET. The parameters considered in this paper for the design optimization includes the sizing of inductor, capacitor, switching frequency, and the bounds of constraints that takes into consideration the continuous conduction mode (CCM) of operation, bandwidth, and ripple content in output current and voltage. The boost DC-DC converter's optimal design is considered as a single optimization problem. The following section completes the mathematical formulation of the objective function and the state space model of the converter.

2.1. Steady state space model of the DC-DC boost converter

Figure 1 shows the electrical circuit diagram of the DC-DC boost converter. When utilized for maximum power point tracking (MPPT) in photovoltaic (PV) systems, the DC-DC boost converter provides high tracking efficiency under adverse circumstances [24], [25]. They also ensure better utilization of energy storage and distribution [26], [27]. The total power loss considering the operating states of the converter, the constraints of ripple in current and voltage levels along with the CCM and bandwidth constants are considered for the optimization problem. The authors have presented the same in much detail in [19] for the improvement of a DC-DC buck converter's design. The governing equations in the modelling using the state vector approach is given by [28], [29].

$$x = \begin{bmatrix} i_L \\ v_C \end{bmatrix} \tag{1}$$

$$\frac{di_L}{dt} = \frac{-v_C}{L}(1-u) + \frac{V_i}{L}u \tag{2}$$

$$\frac{dv_C}{dt} = \frac{i_C}{C}(1-u) - \frac{V_C}{RC} \tag{3}$$

Where, i_L in (1) represents the current flowing in the inductor and output voltage is given by V_C. The switch state is represented by the parameter u in (2) and (3) where the on state (u=1) (under this condition the Q_1 is on and D_1 is inactive) and OFF state (u=0) (under this condition Q_1 is off and D_1 is active) determine the operation of the switching device. The initial value of u functions as the control signal to regulate how the converter operates. The circuit parameters representing the inductor, capacitor, input voltage, and load resistance are denoted by L, C, V_i, and R respectively.
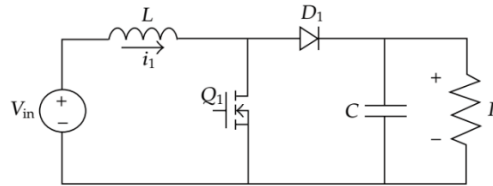

Figure 1. Electrical circuit of a DC-DC boost converter [30]

The ripple in the current and voltage along with the dimension of the inductor for the CCM operation and the bandwidth limitation impose the constraints to the optimization problem. They are calculated as (4)-(8):

$$\Delta i_L = \frac{DV_i}{Lf_s} \tag{4}$$

$$\Delta v_C = \frac{DV_C}{f_s CR} \tag{5}$$

$$Lf_s = \frac{V_C}{2I_O}D(1-D)^2 \tag{6}$$

$$\omega_O = \frac{(1-D)}{\sqrt{LC}} \tag{7}$$

$$\omega_O > 2\pi(af_s) \tag{8}$$

Where the switching frequency is given by $f_s=1/T_s$, Ts being the switching period and fs the switching frequency, and a is a percentage of fs. The total power loss calculations depend on the losses incurred during the converter's operation as well as any losses brought on by parasitic resistance loss and parasitic capacitance induced switching losses. In addition, the device operation loss due to the on-off state transitions at the conclusion of each cycle also effect the power calculation and hence the efficiency of the converter. The equation for the total power loss for one complete cycle of operation of the boost converter denoted by P_{BOOST} is given as (9)-(15):

$$P_{Q1} = P_{ON} + P_{SW} \tag{9}$$

$$P_{ON} = \left(\left(\frac{I_O}{1-D}\right)^2 + \frac{\Delta i_L^2}{12}\right)DR_{DS} \tag{10}$$

$$P_{SW} = (V_C - V_f)\left(\frac{I_O}{(1-D)} - \frac{\Delta i_L}{2}\right)T_{SWON}f_s + (V_C - V_f)\left(\frac{I_O}{(1-D)} + \frac{\Delta i_L}{2}\right)T_{SWOFF}f_s \tag{11}$$

$$P_d = V_f I_O(1-D) + Q_{rr}^{Schotty}V_C f_s \tag{12}$$

$$P_{ind} = \left(\left(\frac{I_O}{1-D}\right)^2 + \frac{\Delta i_L^2}{12}\right)R_L \tag{13}$$

$$P_{cond} = \left(I_{effc}\right)^2 R_C \tag{14}$$

$$P_{BOOST} = P_{Q1} + P_d + P_{ind} + P_{cond} \tag{15}$$

The effectiveness of a converter is determined as (16):

$$\eta = 100 \frac{P_{LOAD}}{P_{LOAD} + P_{BOOST}} \qquad (16)$$

P_{LOAD} represents the output power of the converter. While the ON time and OFF time for the converter is represented by T_{SWON} and T_{SWOF} respectively. IO gives average output current, while R_{DS} provides the MOSFET's on state resistance. The inductor's loss component is represented by R_L and corresponding series resistance is shown for the capacitor by R_C.

2.2. Mathematical formulation of the optimization problem

Optimal selections of converter design parameters, i.e., to set up the optimization problem, the objective function is to be framed subject to operational constraints. The current problem at hand encompasses solving the optimization problem to achieve minimized operational losses in the DC-DC converter, or for P_{BOOST} to be minimal. The constraints considered are the constraints on the design variables maximum and minimum values, the ripple constraints, the CCM operation criterion as (4)-(6), and the bandwidth constraint as (8). The mathematical representation of the minimizing P_{BOOST} has the following constraints as (17)-(21):

$$L_{min} \leq L \leq L_{max} \qquad (17)$$

$$C_{min} \leq C \leq C_{max} \qquad (18)$$

$$f_{smin} \leq f_s \leq f_{smax} \qquad (19)$$

$$\Delta i_L \leq a I_O \qquad (20)$$

$$\Delta v_C \leq b V_C \qquad (21)$$

CCM constraint as (6) and bandwidth constraint as (8). Where a and b are the limits on the percentage averaged magnitude of current and voltage.

3. ALGORITHMS FOR OPTIMIZATION

Optimization algorithms have been used for solving a number of complex problems in the field of engineering [31]. The no-free lunch theorem states that no method can effectively address every optimization problems [32]. In other words, there is no single, all purpose algorithm that can address optimization issues with equal efficacy. The following sub-sections introduce theory of GWO algorithm and discusses the philosophy behind the algorithm's inspiration and formulation.

3.1. Grey wolf optimizer

Mirjalili *et al.* [31] developed the GWO algorithm, which is based on the inspired learning in nature from the behavior of the pack characteristic in grey wolves (canis lupus). This algorithm formulates the leadership and hunting abilities into an optimization framework. On an average a pack of wolves of the species usually have 5-12 members with a dominance hierarchy and the algorithm exploits this trait for the optimization process. The grey wolves have the alpha (α) as leader of the pack. The α leads the pack and may not always be the strongest member in the pack. It is responsible to guide the pack when they are hunting for a prey. The beta (β) wolf is usually the second in command followed by the α in the pecking order is responsible for maintaining the hierarchical order in the pack and provide assistance to the α in the form of feedback. The omega (ω) is the wolf having the lowest ranking within the hierarchy. The delta (δ) wolf includes all those members of the pack other than the α, β, or ω. These include the scouts, hunters, caretakers, sentinels, and elders. In this algorithm, the order of preferred solutions is $\alpha > \beta > \delta$. The remainder of the solutions are considered to be ω. The ω wolves are at the bottom of the hierarchy pyramid. The mathematical representation of hunting to encircle the prey is formulated as (22) and (23):

$$\vec{D} = \left| \vec{C}. \vec{X_P}(i) - \vec{X}(i) \right| \qquad (22)$$

$$\vec{X}(i+1) = \vec{X_P}(i) - \vec{A}. \vec{D} \qquad (23)$$

Where $\vec{X}$ and $\vec{X_P}$ indicate the vectors that contain the position of the grey wolf and the prey, *i* indicates the current iteration count. Coefficient vectors $\vec{A}$ and $\vec{C}$ are numerically calculated as (24) and (25):

$$\vec{A} = 2 \cdot \vec{a} \cdot \vec{r_1} - \vec{a} \tag{24}$$

$$\vec{C} = 2 \cdot \vec{r_2} \tag{25}$$

The vectors r_1 and r_2 are random parameters have values in the range [0,1] and vector $\vec{a}$ is linearly decreased from 2 to 0 over the course of iterations. In (22) and (23) mathematically express the positional updating of the pack members around the prey in any random manner. In nature the α grey wolf leads the pack in hunting and others follow its lead. To mathematically formulate this behavior, we assume that prior information on the location of the prey is available to the α and given that knowledge based on where the prey is positioned, the β and δ wolves update their position accordingly. Three best solutions are marked which represent the α, β, and δ values, while the remaining search agents in the pack update their position accordingly. This is given as (26)-(28):

$$\vec{D_\alpha} = |\vec{C_1}\vec{X_\alpha} - \vec{X}| \tag{26}$$

$$\vec{D_\beta} = |\vec{C_2}\vec{X_\beta} - \vec{X}| \tag{27}$$

$$\vec{D_\gamma} = |\vec{C_3}\vec{X_\gamma} - \vec{X}| \tag{28}$$

The grey wolves adjust their location during hunting, which is given as (29)-(31):

$$\vec{X_1} = \vec{X_\alpha} - \vec{A_1}.(\vec{D_\alpha}) \tag{29}$$

$$\vec{X_2} = \vec{X_\beta} - \vec{A_2}.(\vec{D_\beta}) \tag{30}$$

$$\vec{X_3} = \vec{X_\gamma} - \vec{A_3}.(\vec{D_\gamma}) \tag{31}$$

Mathematically the best position or candidate solution in the current iteration acts as a tool for updating the grey wolf's locations is given as (32):

$$\vec{X}(i + 1) = \frac{\vec{X_1} + \vec{X_2} + \vec{X_3}}{3} \tag{32}$$

The parameter $\vec{A}$ is responsible for the exploration and exploitation of the algorithm.

4. RESULTS AND DISCUSSION

The range of the design parameters and the constraints of the optimization problem considered have been taken from [33] for all values as listed in Table 1. Utilizing the GWO optimization technique, the optimal combination of design parameters is determined for the DC-DC boost converter in a manner that total operational losses are at a minimum. The converter design problem is formulated in the octave [34] simulation software for the constraint based power minimization of the DC-DC boost converter. Because the optimization techniques are stochastic, each of the algorithms modelled are run for a minimum of 100 iterations. The population size or number of search agents, moths, particles, and fireflies are all considered to be equal to 30 for GWO, MFO, PSO, and FFA to have consistency in evaluation of the performance of the algorithms. Comparison is made based on the statistical performance parameters that include the best value, average value, worst value, standard deviation, computational time, no of hits, and the p-value. The results are presented in Table 2.

Table 1. Design parameters and constraints as inputs considered for optimization

Parameter	Value	Parameter	Value
Input voltage	5 V	Range of inductor values	(0.1 μH–100 mH)
Output voltage	10 V	Range of capacitor values	(0.1 μF–100 μF)
Output current	2 A	Range of switching frequency values	(10 kHz-800 kHz)
On state resistance of MOSFET	5.2 mΩ	Reverse recovery charge in diode	50×10^{-9} A
Converter on time	10^{-8} s	Percentage average of current	15% of I_0
Converter off time	10^{-8} s	Percentage average of voltage	15% of V_0
Forward voltage drop on the body of diode	0.9 V		

Table 2. Optimized P$_{Boost}$ values of the DC-DC boost converter by GWO, MFO, PSO, SA, and FFA

Algorithm	Best value (W)	Average value (W)	Worst value (W)	Standard deviation	Computational time (sec)	No of hits	P-value
MFO	1.75388	1.75389	1.75421	3.41497E-5	0.692	92	7.33e-14
PSO	1.75388	1.75388	1.75388	3.37486E-13	0.693	90	3.87e-09
SA	1.75504	1.75399	1.78652	0.00394	1.386	88	1.00e-29
FFA	1.76141	1.76109	1.77104	0.00331	4.401	85	3.95e-32
GWO	1.75388	1.75389	1.75395	1.03211E-5	0.655	95	-

From Table 2, the best value and optimized solution to the DC-DC converter is 1.4085 W (P$_{BOOST}$). And therefore, the overall efficiency of the converter designed is 98.12%. It is also observed that all the optimization algorithms reach this result which indicates that the global optimum has been attained. The results obtained are best for the GWO considering the standard deviation as well as requiring the minimum the computational time for 100 iterations for each run of the algorithms. While the average values are also seen to be equal for the GWO, MFO, and PSO, however in terms of standard deviation and worst values within the 100 runs considered, GWO clearly outperforms MFO and PSO. Figure 2 shows the convergence characteristics of all the algorithms for their best runs. It is clearly evident that the GWO takes the lowest no of iterations to reach the minima, thus establishing its superiority when compared with the other algorithms.

Table 3 compares the optimal outcomes achieved by various optimization methods. It can be observed that the best optimized result is attained with the GWO with lowest power loss and highest efficiency in the converter design. The more significant finding is that the optimized design uses the lowest value of filter inductor, among the algorithms which is often the limiting criterion when considering the converter economics [35]. The obtained results also indicate an improvement in the design when compared with the work of [33] from three aspects namely, the optimized power loss in the converter, the efficiency, and filter inductor. This indicates the efficacy of GWO for finding an improved optimized result for minimizing the power loss by 16%, which is a significant improvement.
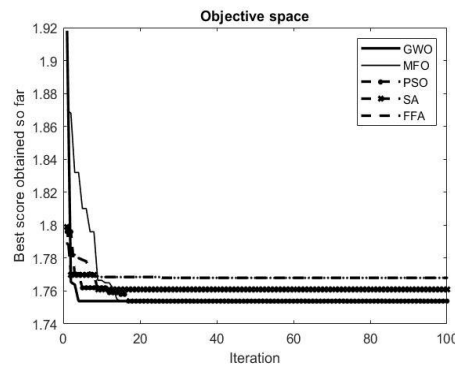

Figure 2. Convergence curve of the GWO, MFO, PSO, SA, and FFA

Table 3. Optimized design parameter values of the DC-DC boost converter by GWO, MFO, PSO, SA, FA, and GP

Algorithm	P$_{BOOST}$ (W)	L (mH)	C (μF)	Fs (kHz)	η (%)
GP [33]	2.097	79.95	95.946	104.23	90.5
MFO	1.75389	9.97	100	100.03	91.91
PSO	1.75388	10	100	100.00	91.91
SA	1.75504	7.91	94.8	109.25	91.91
FFA	1.76141	6.21	100	100.02	91.92
GWO	1.75389	6.21	100	100.02	91.93

4.1. Solution quality

The statistical assessment of the GWO is carried out using the Wilcoxon rank sum test. The test is used to find the statistically significant results obtained at the end of the optimization process which translates in our situation, to the optimized objective value at the end of the iterative process. The test detects the substantial variation in the results of two algorithms when applied pairwise. For an algorithm to show sufficient satisfactory results, evidence from the results should conclusively indicate that the null hypothesis doesn't hold true. The P-value, which is less than 0.05, provides strong evidence to refute the null hypothesis.

The P-value for all the pairwise test cases for the statistical parameters shows values significantly less than 0.05 thus indicating the statistical significance of the results and thereby establishing the GWO as the best algorithm suitable for the design optimization problem.

4.2. Robustness

In the case of optimization algorithms which are rooted in nature, evolutionary behavior in the initialization phase is always random while computational tools are used. This makes it imperative that to truly classify an algorithm to be robust, repeated trials are to be conducted to ascertain the consistency of the obtained results. The GWO algorithm was evaluated for a total of 100 runs along with the rest of the algorithms as well. It was also compared for the number of times it gave the minimized value of the PBOOST for a minimum of 95 times before the other algorithms taking the least number of iteration steps. This indicates that the error in obtaining the optimized result is limited to 5%, indicating a very consistent performance when compared to other algorithms.

5.   CONCLUSION

In this paper, the GWO was used for the DC-DC boost converter design optimization. The design parameters considered were the dimensions of the inductor, capacitor, operating switching frequency, and converter duty ratio. The problem of minimization of the overall operational losses is studied keeping the constraints of CCM and bandwidth and ripple content. The algorithms performance is compared to other well-known optimization techniques published in the scientific literature namely MFO, PSO, SA, and FA. The computational speed, consistency of results, solution quality, and robustness make the superior performance of the GWO compared to other algorithms the best algorithm to be used for the solution of the problem under consideration.

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