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Article

Optimizing weighted voltage mode control for enhanced output cross-regulation in multi-output DC/DC converters

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ABSTRACT

Weighted voltage mode control is a widely used method for regulating multiple output DC-DC converters, but inconsistent outcomes are often observed in design due to the complexity of the weighting variable optimization. This study proposes an optimization-based approach to accurately estimate the optimal weighting factors for improved output voltage regulation in multiple output forward DC-DC converters. Three optimization algorithms, the Imperialist Competitive Algorithm (ICA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) are compared for their speed and accuracy in estimating the weighting factors. Additionally, a Fuzzy Logic Controller (FLC) is used to further reduce the overall steady-state error and improve transient characteristics. Simulations are performed using the MATLAB/Simulink software, and the results show that the proposed strategy significantly enhances output cross-regulation in multiple output forward DC-DC converters. The ICA-based weighting factor estimator is found to be the most effective algorithm among the three optimization algorithms tested. The main contribution of this study is to provide a more efficient and accurate method for estimating the weighting factors in multiple output forward DC-DC converters, which can lead to improved performance and reliability in various applications.

1. Introduction

Multiple-output DC-DC converters are widely used in various applications due to their higher efficiency than several separate single-output power supplies [1]. Among different topologies, multiple output forward DC-DC converters are commonly used, especially in renewable energy systems [2]. However, poor regulation is one of their main limitations, which can be addressed by using the weighted voltage mode control method [3-5]. In this method, the regulation error is modified by changing the weighting factors used in the control, which redistributes the error among the outputs of the converter [7-8]. Although this method has been employed in some research, the weighting factors have typically been determined by trial and error, resulting in inconsistent outcomes [9-10]. To overcome this limitation, this paper proposes the use of optimization algorithms to determine the optimal weighting factors for efficient control of the output voltages of multi-output DC-DC converters. The Imperialist Competitive Algorithm (ICA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) algorithms are employed to concurrently determine the best weight values and ideal duty cycle arrangement for enhanced regulation of all outputs [11-17]. The effectiveness and capability of the proposed algorithm in determining the ideal design are demonstrated in this paper. The proposed approach is not limited to the forward converter but can be applied to any isolated or non-isolated converter or any inverter. Moreover, to improve the steady-state inaccuracy and transient characteristics, the duty cycle is controlled by a fuzzy logic controller (FLC) [18-19]. The proposed approach is described in detail in Section 2, followed by a description of the evolutionary algorithm-based weighting factor in Section 3. The results and discussions are presented in Section 4, and the conclusions are provided in Section 5. In summary, this paper presents a general, quick, and accurate approach to determining the weighting factors required for efficient control of the output voltages of multi-output DC-DC converters. The proposed approach is expected to enhance the dc cross-regulation and dynamic characteristics of the outputs, leading to improved performance and efficiency in various applications.

2. The proposed control method description

In this research, we consider a forward topology with three outputs and a weighted error voltage mode control strategy. The reference voltages of all three output voltages are measured and compared, and the error is multiplied by three weight factors to achieve the desired output voltage levels. To optimize the system's performance during operation, we utilize computational techniques such as Imperialist Competitive Algorithm (ICA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) to determine the best suitable parameters for the system. These algorithms repeatedly attempt to increase the quality of a potential solution, resulting in significantly improved performance of the suggested tuned controller compared to the use of fixed factors for effective regulation. The optimization algorithms are used to determine the optimal weighting factors for the weighted error voltage mode control. The described techniques are iterated by the optimization algorithms until they achieve the best result for the objective function's minimization. In each of the cases, the population under control is equal to 50. To further improve the system's transient properties and reduce overall steady-state inaccuracy, a fuzzy logic controller is also employed. The proposed approach and the system block diagram are shown in Figure 1. The power unit, control unit, and weighting factor estimation unit are the three main components of the proposed system's topology. Following are full introductions of the power unit and control unit. The section 3 presentation also includes the unit for estimating the weighting factor.

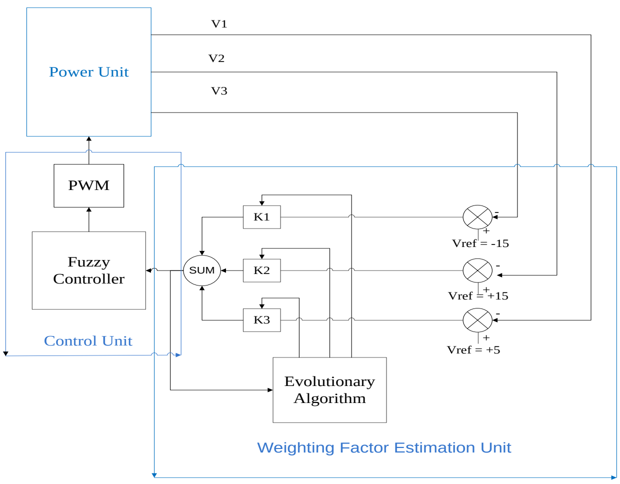


Figure 1. The proposed control strategy

2.1 Power unit

Switching transistors (which include two switching MOSFETs), a high-frequency transformer, output rectifiers, and output filters make up the power stage block. Using an input voltage range of 18V to 40V dc and a switching frequency of 50 kHz, this study considers a converter with three outputs (5V/50W, 15V/45W, and -15V/15W). By linking the output filter inductors, the cross-regulated outputs' transient characteristics can be improved. Fig.2 shows these multiple outputs forward DC-DC converters. This circuit uses a single DC input (nominally 28 Volt) and converts to three simultaneous output voltages.

R_{w1} and R_{wi} are the primary and secondary winding resistances, respectively, in Figure 2. r_d is the source resistance. The resistance of D_1 in its ON state is R_f. The ON state resistance of switching MOSFETS is represented by R_{ONQ1} and R_{ONQ2}, respectively. The primary and secondary leakage inductances are L_{11} and L_{22}, respectively. The MOSFETS leakage inductances are L_{Q1} and L_{Q2}, respectively. The output capacitor's Equivalent Series Resistor (ESR) is designated as r_{ci} [20].

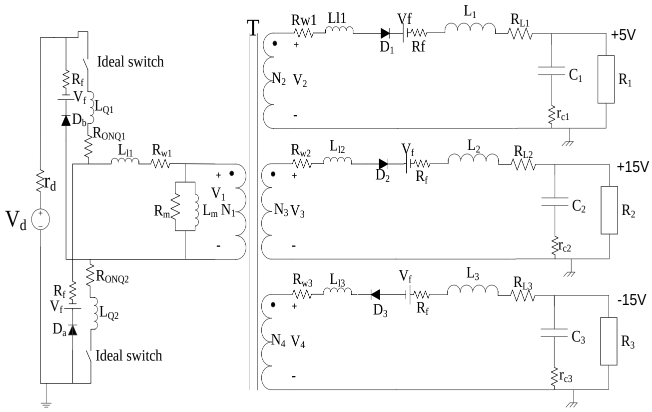


Figure 2. Multiple outputs forward DC-DC converter

2.2 Control unit

The control unit consists of a Fuzzy Logic Controller and Pulse-Width Modulation (PWM) generator. The PWM approach is used to regulate the power switches, and fuzzy logic is used to generate the pulses.

2.2.1 Fuzzy logic controller

A dc-dc forward converter has been controlled by employing fuzzy control. Nonlinear time-variant systems are well suited for fuzzy controllers, which do not require an exact mathematical model of the system to be controlled. They are typically created using the knowledge of the converters obtained from experts [20]. Error signal and differential error signal are the inputs of the FLC. The switching signal's duty cycle is the output.

$$E(t)=V_{ref} - V_o(t) \quad (1)$$

$$dE= E(t)- E(t-1) \quad (2)$$

$$dD= D(t) – D(t-1) \quad (3)$$

where V_{ref} is reference voltage, $V_o(t)$ is output voltage at t^{th} instant, $E(t)$ and $E(t-1)$ are error signal, at t^{th} and $(t-1)^{th}$ instant, respectively. $D(t)$ and $D(t-1)$ are duty cycle at t^{th} and $(t-1)^{th}$ instant, respectively. dE and dD are changed in error and duty cycle, respectively.

For this application, a controller of the Mamdani type is used. The max-min inference approach is employed to determine the control decision. In order to get a clear result from the linguistic values produced using the rule basis, the center of gravity approach to defuzzification is also utilized. The basic rule of this type of controller is: IF E is A and dE is B THEN $d(t)$ is C, where A and B are fuzzy subsets, C is a fuzzy singleton. According to Figure 3, the input error, change in error, and output all have triangle membership functions. Table 1 serves as an illustration of the 7*7 inference system that was utilized to generate the fuzzy controller.

N stands for negative, P for positive, and Z for zero in Table 1. B stands for big, M for medium, and S for small. NB, for instance, stands for negative big.

Table 1. Rule base used in the fuzzy controller

E\dE	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

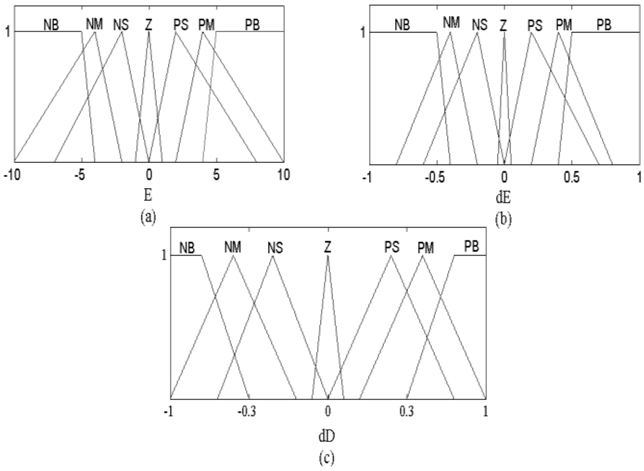


Figure 3. Membership functions of (a) input E; (b) input CE; (c) output dD

2.2.2 Pulse width modulation (PWM)

In a DC-DC converter with fuzzy logic control, the desired duty cycle is computed by the fuzzy logic controller using the total steady-state error. The Pulse Width Modulation (PWM) then generates the pulse signals for the converter based on the desired duty cycle. The duty cycle serves as the control input and is a logic signal that regulates the power stage's pattern, which in turn controls the output voltage. By adjusting the duty cycle, the converter can maintain the desired output voltage, even in the presence of disturbances or changes in the input voltage.

3. Evolutionary algorithm-based weighting factor estimator

To achieve effective regulation of each output in a multiple-output DC-DC converter with weighted voltage mode control, the weighting factor (Ki) plays a critical role in addition to the circuit parameters. In this paper, we propose to use optimization algorithms, namely ICA, PSO, and ACO, to estimate the optimal weighting factors for all three output voltages. These algorithms iterate through the steps outlined until they find the optimal solution to minimize the fitness function and improve the regulation performance of each output. The algorithm fitness function is assumed to correspond to the output errors. The following is how it is expressed as the sum of the absolute terms of the relative errors:

$$\boldsymbol{FitnessFunction} = |\boldsymbol{e}_{+15}| + |\boldsymbol{e}_{+5}| + |\boldsymbol{e}_{-15}| \qquad (4)$$

Where e_{+5} is the +5-v output error, e_{+15} is the +15-v output error, and e_{-15} is the -15 v output error. An evolutionary algorithm is a subset of evolutionary computation, a population-based metaheuristic optimization method used in artificial intelligence.

3.1 Imperialist competitive algorithm (ICA)

The ICA algorithm used in this study is inspired by human socio-political evolution and is based on the idea of colonial competition. In the algorithm, a group of imperialist countries, along with their colonies, competes to find the general optimal solution for the optimization problem. In this study, the number of initial imperialist countries is set to Np=20, and the number of established colonies is set to Nc=50. The stopping criterion is defined as reaching the maximum number of iterations (Max Iteration=100) and having only one imperialist left in the search space. The ICA flowchart is shown in Figure 4.

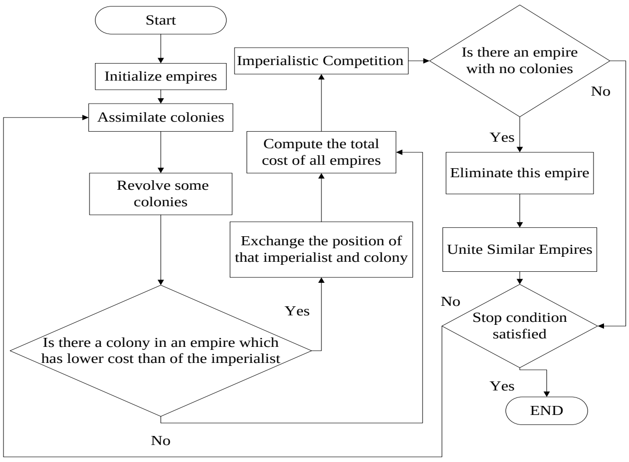


Figure 4. Flowchart of ICA

3.2 Particle swarm optimization (PSO)

PSO can be applied to problems whose answer is a point or surface in the next n space. It is in this space that hypotheses are formed, given an initial velocity and given channels of particle communication. Then, when these particles travel in the answer space, the outcomes are computed each time based on a "goal function." Particles gradually move faster in the direction of other particles that belong to the same communication group and have a higher competency standard. Each agent is aware of its current best value (pbest) and its XY position. Additionally, each agent is aware of the group's best value (gbest) among all the pbest s. By initializing the *swarm* from the solution space, the velocity and position of all particles are randomly set to within determined ranges. The velocities of every particle are updated after every iteration. The following equation provides for the modification of each agent's velocity [12, 13]:

$$v_{i+1} = v_i + c_1 R_1 (p_{i,best} - x_i) + c_2 R_2 (g_{i,best} - x_i) \qquad (5)$$

where x_i and v_i represent a particle's current position and speed, respectively. The uniformly distributed random numbers [0-1] that introduce the stochastic component are R1 and R2. Weight is controlled by the variables c_1 and c_2. The equation can be used to determine a specific velocity that gradually approaches the pbest and gbest values that have been determined by all of the particles in the swarm. The position update equation is given by:

$$\boldsymbol{p_i new = p_i + v_i} \tag{6}$$

After updating, p_i should be checked and limited to the allowed range. Afterwards, when the condition is met Update $p_{i,best}$ and $g_{i,best}$ as follows:

$$\boldsymbol{p_{i,best} = p_i \qquad if\ f(p_i) > f(p_{i,best})}$$

$$g_{i,best} = g_i \qquad if\ f(g_i) > f(g_{i,best}) \tag{7}$$

where *f(x)* is the objective function to be optimized. When stop conditions were met, algorithm reports the values of $g_{i,best}$ and $f\ (g_{i,best})$ as its solution. The method continues until a successful outcome is achieved or the specified number of iterations has been reached.

3.3 Ant colony optimization (ACO)

One of the most current methods for approximate optimization is ACO [14-17]. In this method (ACo), artificial ants by moving on the problem diagram and by leaving marks on the diagram, like real ants that leave marks in their path, make the next artificial ants can provide better solutions to the problem. Also in this method, the best path in a diagram can be found by computational-numerical problems based on probability science. An ant encountering an already established route can identify it and decide to follow it with a high probability, exploitation, and as a result, reinforces the track with its own pheromone. In contrast, an isolated ant virtually walks at random, exploring.

4. Results and discussions

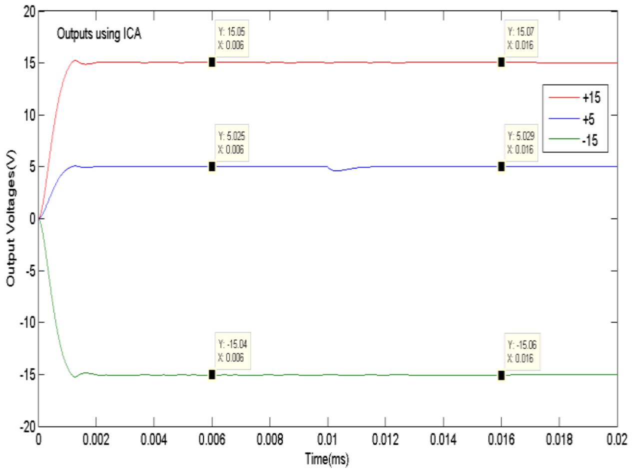
In this section, several conditions were taken into consideration and simulated in order to assess the accuracy and validity of the suggested method. The simulation results of three optimization algorithms and conventional constant weighting factor control are presented. The following conditions are used to run the simulations in the MATLAB/SIMULINK environment:

- Variation of DC-DC converter output load (at +5 V output)
- Variation of DC-DC converter output load (at +15 V output)
- Variation of DC-DC converter input voltage

It should be noted that the fuzzy logic controller has been used for all approaches including constant weighting factors (which were calculated by conventional mathematical method) and all three proposed methods at three mentioned conditions. Also, for the same system, a PID controller is designed. When the PID coefficients are established for the investigated DC-DC converter by trial and error, the total error is then sent through a PID controller to reduce the steady-state error as well as a fuzzy logic controller in Section 4.5. Under the following circumstances, simulations are carried out in the MATLAB/SIMULINK environment. Also in this section, the performances of the three used algorithms are compared with each other.

4.1 Variation of DC-DC converter output load (At +5 V output) from 100% to 50%

In this case, the load on +5 v output of the converter changes from 100% to 50% at t=10 ms when the output voltages are in steady state. Figure 5 (a) shows three output voltages when ICA is used as a weighting factors estimator. Figures 5 (b) and (c) show these output voltages for ACO and PSO weighting factors estimator, respectively. Accordingly, Figure 5 (d) shows these voltages for constant weighting factor are used for voltage mode weighting factor control. These results show that the use of an evolutionary algorithm can improve the percent of cross-regulation significantly.



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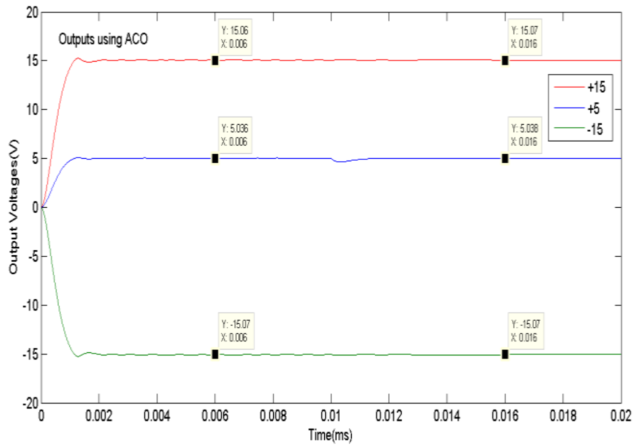

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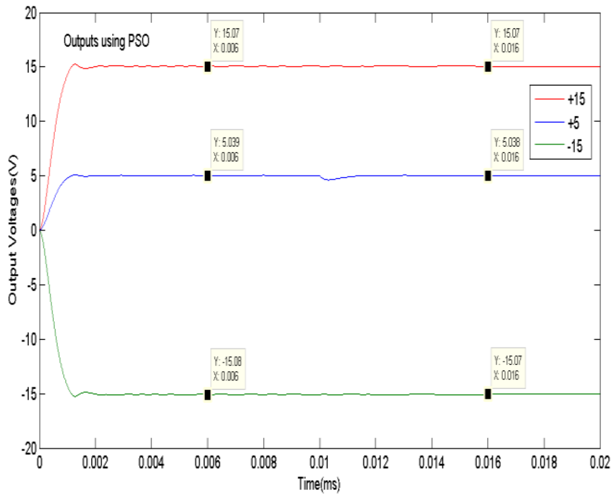

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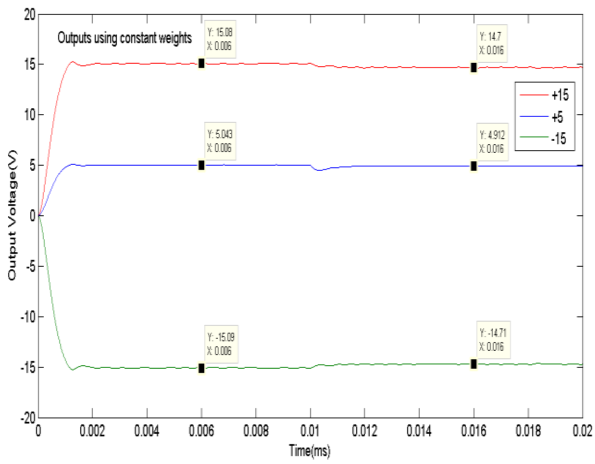


(d)

Figure 5. Output voltages while load on +5 V output changes from 100% to 50% with a) ICA estimator of weighting factors, b) ACO estimator of weighting factors c) PSO estimator of weighting factors, d) constant weighting factors (Continue)

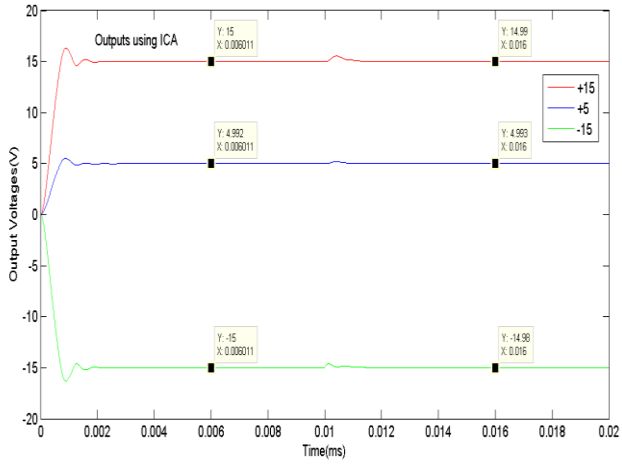
Table 2 shows the regulation of the presented methods before and after load changing. In a constant weighting factor method, the weighting factors are determined by trial and error at the system condition before load changing (as t=6 ms) for optimum regulation. Thus, the regulation can be good in this condition, but after changing conditions, regulation may be reduced, whereas three other methods have lower regulation. Also, because of its higher accuracy and speed, ICA based weighting factor estimator is more effective in comparison with ACO and PSO-based weighting factor estimators.

Table 2. Output voltage regulation while load changes at +5 v output from 100% TO 50%

Method	**Regulation (%) at t=6 ms**			**Regulation (%) at t=16 ms**		
	+15V	**+5V**	**-15V**	**+15V**	**+5V**	**-15V**
ICA	0.33	0.50	0.26	0.46	0.58	0.40
ACO	0.40	0.72	0.46	0.46	0.76	0.46
PSO	0.46	0.78	0.53	0.46	0.76	0.46
Constant Weighting Factor	0.53	0.86	0.60	2	1.76	1.93

4.2 Variation Of DC-DC converter output load (At +15 V output) from 100% To 120%

In the third case, the load on +15 v output of the converter changes from 100% to 120% at t=10 ms when the output voltages are in a steady state. Figures 6 (a), (b), (c), and (d) show the three output voltages for the ICA, ACO, and PSO-based estimator of the weighting factor as well as the constant weighting factor method, respectively. Table 3 shows the output voltage regulation. This outcome demonstrates that the suggested approach can enhance cross-regulation in all three outcomes. Results show that the ICA can be more accurate than the two other algorithms.



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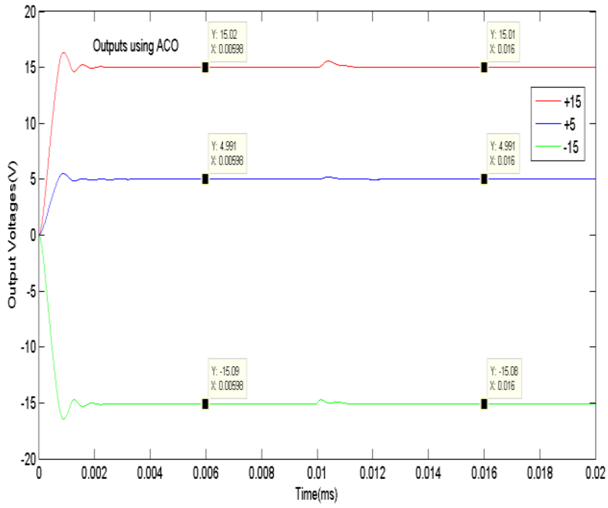

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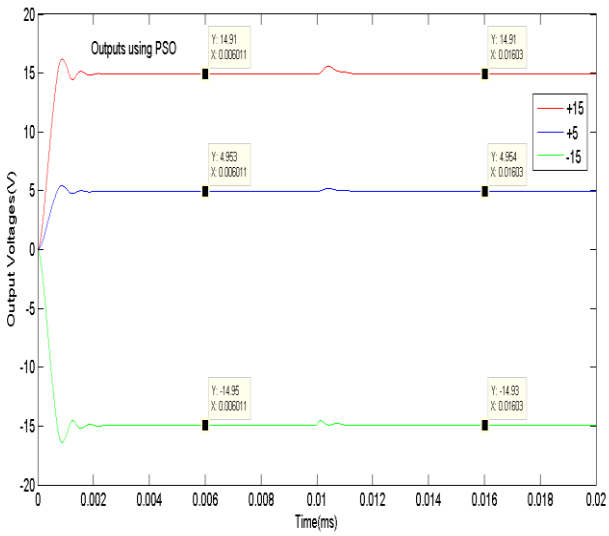

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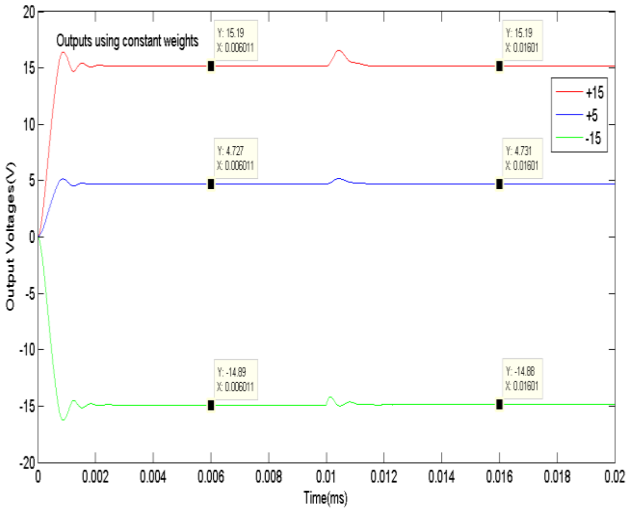


(d)

Figure 6. Output voltages while the load on +15 V output changes from 100% to 120% with c) PSO estimator of weighting factors, d) constant weighting factors (Continue)

Table 3. Output voltage regulation while load changes at +15 v output from 100% to 200%

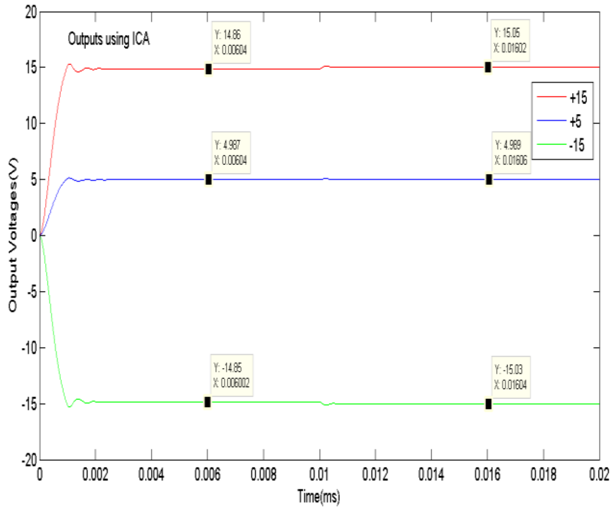
Method	**Regulation (%) at t=6 ms**			**Regulation (%) at t=16 ms**		
	+15V	**+5V**	**-15V**	**+15V**	**+5V**	**-15V**
ICA	0.00	0.05	0.00	0.06	0.14	0.13
ACO	0.13	0.18	0.60	0.06	0.18	0.53
PSO	0.60	0.94	0.33	0.60	0.92	0.46
Constant Weighting Factor	1.26	5.46	0.73	1.26	5.38	0.80

4.3 DC-DC Converter Input Voltage Changing From 30 V to 35 V

In this case, the input DC voltage of the DC-DC converter changes from 30V to 35V. Figures 7 (a), (b), (c), and (d) show the three output voltages for the ICA, ACO, and PSO-based estimator of the weighting factor as well as the constant weighting factor method, respectively. The results of this case show that the evolutionary algorithms are very effective in improving cross-regulation in all outputs. Results after changing at t=16 ms show that the constant weighting factor method is not a suitable method for all conditions. The results of regulation for comparison of all methods are presented in Table 4.

4.4 Dynamic Response Comparison

The +5 V output voltage results of the mathematical-based weighting factors estimator, together with a set of optimal weighting factors that is obtained from one of the best-used evolutionary algorithms (ICA), are presented in Figure 8 when both PID and fuzzy logic controllers are compared, their performances have been assessed through simulations. The time response parameters percent overshoot (%), settling time (ms), and percent steady-state error (%) for PID controller and fuzzy logic controller when ICA and conventional mathematical method have been used for both as weight factor estimator, are presented in Table 5.



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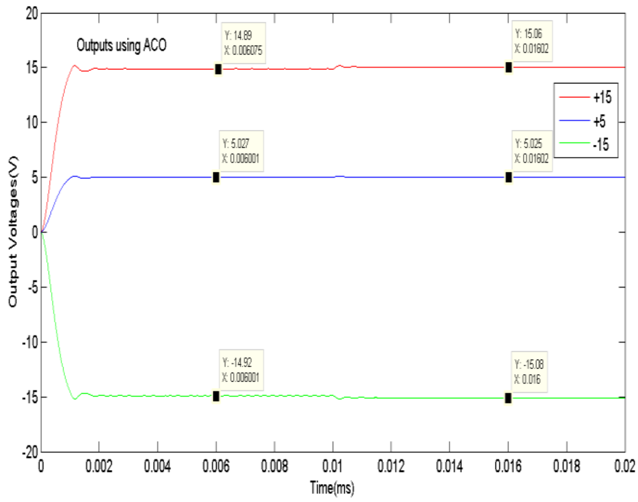

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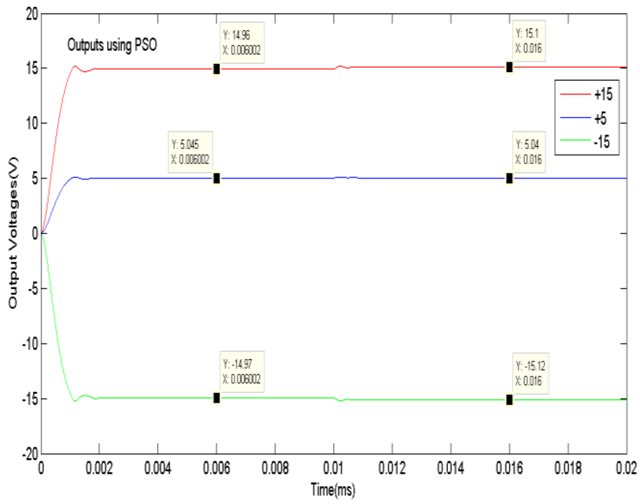

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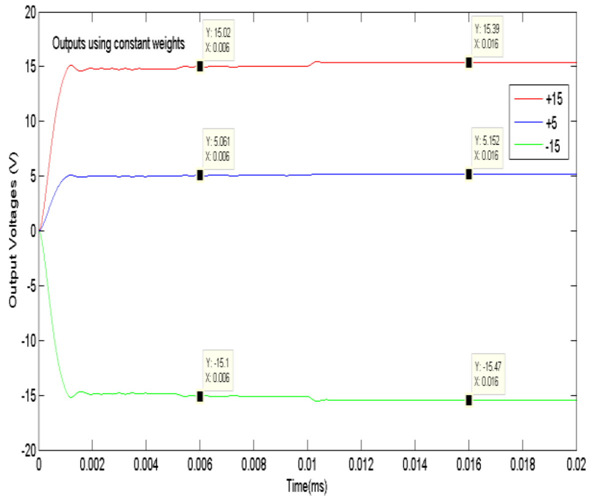

(d)

Figure 7. Output voltages while input voltage changes from 30 V to 35 V with a) ICA estimator of weighting factors, b) ACO estimator of weighting factors, c) PSO estimator of weighting factors, d) constant weighting factors (Continue)

Table 4. Output voltage regulation while input voltage changes from 30v to 35v

Method	Regulation (%) at t=6 ms			Regulation (%) at t=16 ms		
	+15V	+5V	-15V	+15V	+5V	-15V
ICA	0.93	0.26	1.00	0.33	0.22	0.20
ACO	0.73	0.54	0.53	0.40	0.52	0.53
PSO	0.26	0.90	0.20	0.66	0.80	0.80
Constant Weighting Factor	0.13	1.22	0.66	2.26	3.04	3.13

As shown in this Figure 8, the choice of appropriate weighting factors, in addition to improving voltage regulation, can positively affect the dynamic behavior of the system. Results show that when the optimal weighting factors are used, the overshot value and settling time have reduced significantly.

4.5 Comparison of the Presented Algorithms Performances

In this section, the comparative performance analysis of the three optimization algorithms used in this study is presented. Table 6 summarizes the performance of the algorithms under different conditions, with total regulation being the sum of regulation at all three output voltages. Results show that ICA outperforms PSO and ACO in terms of overall regulation, execution time, and convergence rate. Moreover, ICA is found to be more effective in achieving cross-regulation than PSO and ACO. It should be noted that while all optimization techniques improve cross-regulation, ICA shows better results. The simulations were performed using MATLAB on a Pentium 2.4GHz computer with a population size of 50 in all scenarios and a maximum iteration of 50 for all algorithms. The findings suggest that ICA is a suitable optimization algorithm for this work and could be explored further for other applications.

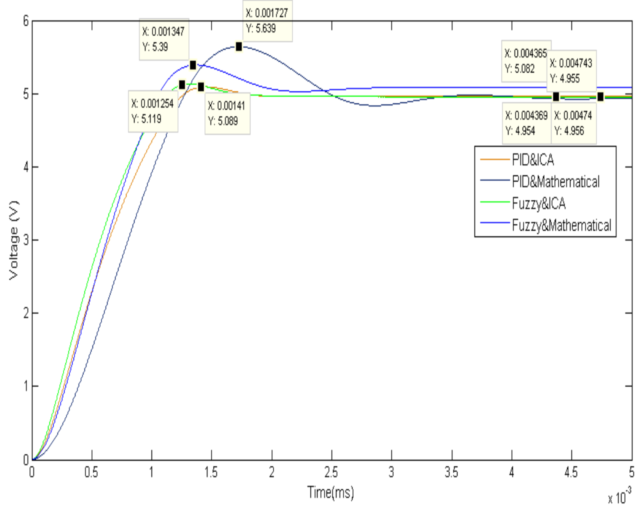

Figure 8. The +5 V output voltage results for Fuzzy ICA, PID ICA, Fuzzy mathematical, and PID mathematical methods

Table 5. Time response parameters

Item / Method	Overshoot (%)	Settling time (ms)	Steady state error (%)
Fuzzy & ICA	2.38	1.9	0.88
PID & ICA	1.78	1.9	0.90
Fuzzy Mathematical	7.8	2.5	1.64
PID & Mathematical	12.78	3.5	0.92

Table 6. Algorithms perform at different conditions

Conditions	Convergence Iteration			Total regulation % at t=16ms		
	ICA	ACO	PSO	ICA	ACO	PSO
Load variation from 100% to 50%	75	85	100	1.44	1.68	1.68
Voltage variation from 30V to 35V	75	80	110	0.75	1.45	2.26
Load variation from 100% to 120%	70	85	110	0.33	0.77	1.98

5. Conclusion

In summary, this paper presents a novel approach for the estimation of weighting factors in weighted voltage mode control of multiple outputs forward DC-DC converter. The approach uses evolutionary algorithms, including Imperialist Competitive Algorithms, Particle Swarm Optimization, and Ant Colony Optimization, to find the optimal weighting factor for voltage mode control. The fuzzy logic controller is also utilized to improve the dynamic response of the converter. The proposed method improves the cross-regulation and dynamic characteristics of the outputs significantly compared to the constant weighting factor method. The ICA-based weighting factor estimator is shown to have higher speed and accuracy compared to the other presented evolutionary algorithms, making it more effective. Overall, the results demonstrate that the proposed method can be used for other types of multiple-output DC-DC converters and can considerably enhance the control and dynamic features of the detected outputs if the weighting factors are properly designed.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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