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Optimal Fuzzy Tuning Using Bacterial Foraging Optimization Algorithm

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ABSTRACT: Positive output elementary Luo converter performs the conversion from positive DC input voltage to positive DC output voltage. Since Luo converters are non-linear and time-variant systems, the design of high performance controllers for such converters is a challenging issue. The controller should ensure system stability in any operating condition and good static and dynamic performances in terms of rejection of supply disturbances and load changes. To ensure that the controllers work well in large signal conditions and to enhance their dynamic responses, soft computing techniques such as Fuzzy Logic controller (FLC) and Bacterial Foraging Optimization Algorithm based FLC (BFOA-FLC) are suggested. Trial and error method is used to find the parameters of fuzzy controller. It is a hard and time-consuming method based on expert knowledge. Hence in this research work, a method based on Bacterial Foraging Optimization Algorithm (BFOA), which simulates the foraging behavior of "E.coli" bacterium is used to tune fuzzy rules, membership functions and scaling gains of FLC. BFOA is employed to search for optimal fuzzy parameters for controlling the output voltage of Luo converter by minimizing the time domain objective function. The performance of the proposed technique has been evaluated with respect to load variations and line variations. Simulation results have shown the validity of the proposed technique in controlling the output voltage of Luo converter under different disturbances.

KEYWORDS: Bacterial Foraging Optimization Algorithm, Fuzzy Logic Controller, Luo Converter, Membership Functions.

I. INTRODUCTION

Fuzzy logic controller (FLC) is an alternative to conventional model-based control schemes. An FLC is basically a model-free control paradigm, where the control signal is calculated by fuzzy inference rather than from the system dynamics. This property makes an FLC suitable for controlling nonlinear, uncertain or ill-understood dynamic systems. It has also been proved that an FLC works well in situations where there is unknown variation in plant parameters.

Recently, nature-inspired optimization algorithms, such as genetic algorithm, particle swarm optimization, bacterial foraging optimization and so forth have attracted considerable attention in various fields because of the of their excellent effectiveness characteristics. Development of bio-inspired swarm intelligence methodologies based on bacterial colony behavior is an emerging research area with similar population and evolution characteristics to those of genetic algorithm. However it differentiates in emphasizing the cooperative behaviour among group member. Swarm intelligence is used to solve optimization and cooperative problems among intelligent agents, mainly in artificial network training, multi objective optimization problems, cooperative and/or decentralized control, etc. Basically, chemotaxisis a foraging behavior that implements a type of optimization where bacteria try to climb up the nutrient concentration, avoiding noxious substances and search for ways of neutral media. Based on these biological concepts, the definition of an optimization model of Escherichia coli bacterial foraging is possible. An optimization algorithm inspired by the social foraging behavior of Escherichia Coli bacteria present in the human intestine. This optimization algorithm has proven to be superior over the other optimization algorithms such as genetic algorithm, particle swarm optimization etc., in terms of faster convergence speed to global optimal solution, better response and less

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computational time requirement. The BFOA as a computational intelligence based technique is very powerful in many control applications especially as non-linearity of systems or size of problems does not largely affect its performance and converge to the optimal solution in many problems where most analytical or gradient based methods fail to converge. BFOA work due to its unique dispersal and elimination technique and can find favourable regions when the population involved is small. These unique features of the algorithm overcome the premature convergence problem and enhance the search capability. Hence, it is a suitable optimization tool for power electronic controllers. This research presents the application of the concept of bio-inspired Bacterial Foraging Optimisation Algorithm (BFOA) to tune fuzzy logic controller parameters for voltage control of Luo converter. The fuzzy membership functions, fuzzy control rules and normalizing and denormalizing gains are optimized using Bacterial Foraging Optimisation Algorithm. The optimization algorithm is implemented by using MATLAB m-file program and linked with the system simulation program in MATLAB-SIMULINK, to check the system performance. The BFOA optimized the fuzzy parameters which give the minimum objective function (ISE).

II. POSITIVE OUTPUT ELEMENTARY LUO CONVERTER (POELC)

Luo converters belong to a series of new DC-DC converters that are developed from the basic converters using the voltage lift technique. Voltage lift technique is a popular method that is applied in electronic circuit design to improve the circuit characteristics. Luo converters overcome the effects of the parasitic elements that limit the voltage conversion ratio. Positive output Luo converter performs the conversion from positive DC input voltage to positive DC output voltage. They work in the first quadrant with large voltage amplification. The elementary Luo converters perform step-down or step-up DC-DC conversion.

The positive output elementary circuit is shown in Fig. 1. Switch S is a N-channel power MOSFET (NMOS) device. It is driven by a PWM switching signal with repeating frequency 'f_s' and duty ratio 'd'. The switching period is $T = 1/f_s$ so that the switch-on period is dT and the switch-off period is $(1-d)T$. The load R is resistive, where $R = V_o/I_o$; V_o and I_o are the average output voltage and current. The elementary circuit consists of a positive Luo pump *S*-L_1-*C*-*D* and a low pass filter L_2-C_0. The pump inductor L_1 transfers the stored energy to capacitor *C* during the switch-off period and then the energy stored on capacitor *C* is delivered to load *R* during the switch-on period. Therefore if the voltage V_c is higher, the output voltage V_o should be higher. When switch *S* is ON, the source current $i_I = i_{L_1} + i_{L_2}$ (Fig. 2). Inductor L_1 absorbs energy from the source and inductor L_2 absorbs energy from the source and capacitor C. Both currents i_{L_1} and i_{L_2} increase when switch *S* is OFF (Fig. 3) source current $i_I = 0$. Current i_{L_1} flows through the freewheeling diode *D* to charge capacitor *C*. Inductor L_1 transfers its stored energy to capacitor *C*. Current i_{L_2}flows through the (C_o-*R*) circuit and freewheeling diode *D* to keep itself continuous. Both currents $i_{L_1}$and i_{L_2} decrease. When switch *S* is turned off, current i_{L_1}flows through the freewheeling diode D. This current descends in the switch-off period $(1-d)T$. If current i_{L_1} does not become zero before switch *S* is turned on again, this working state is defined as the Continuous Conduction Mode (CCM). If current i_{L_1} becomes zero before switch *S* is turned ON again, the working state is defined as Discontinuous Conduction Mode (DCM). The average output voltage of the converter in Continuous Conduction Mode is

$$V_o = \frac{d}{(1-d)} V_I \qquad (1)$$

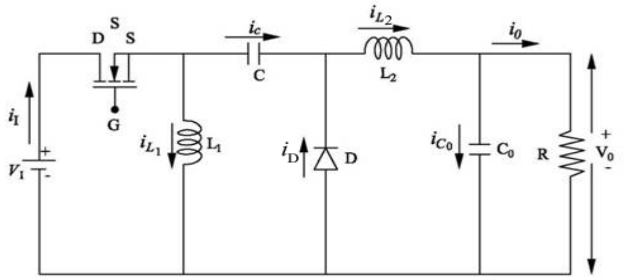

Fig. 1 Circuit Diagram of Positive Output Elementary Luo Converter

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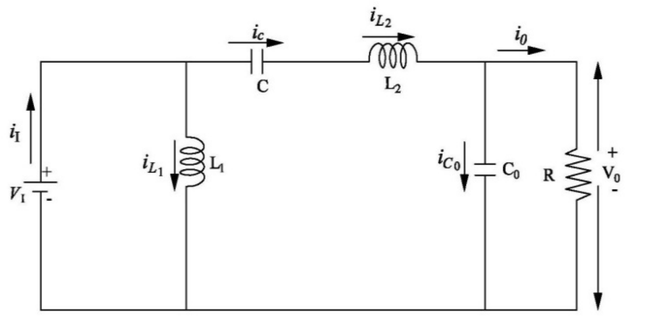

Fig. 2 Equivalent Circuit During Switch-ON (Mode 1)

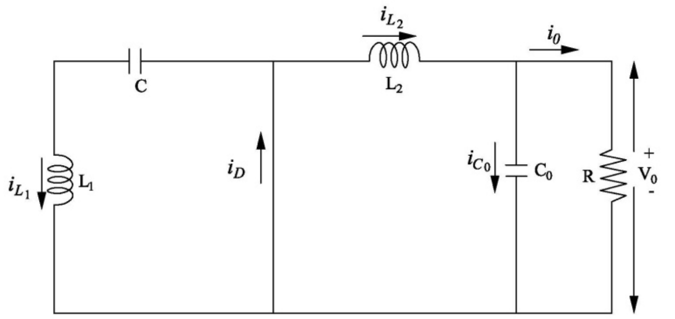

Fig. 3 Equivalent Circuit During Switch-OFF (Mode 2)

III. FUZZY LOGIC CONTROLLER

Fuzzy logic is a form of many-valued logic which is derived from fuzzy set theory. In contrast with "crisp logic", where binary sets have two-valued logic, fuzzy logic variables may have a truth value that ranges in degree between "0" and "1". Fuzzy logic controller is a control tool for dealing with uncertainty and variability in the plant. The implementation of the proposed controller does not require any specific information about the converter model as well as circuit parameters and works independent of the operating point of the Luo converter.

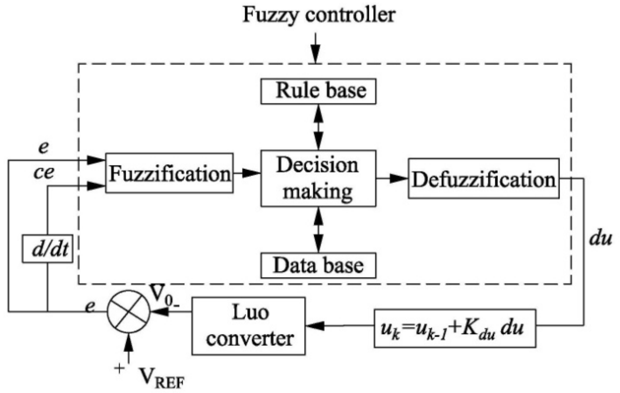

Fig. 4 Block Diagram of Fuzzy Logic Controller for Luo Converter

Design of fuzzy logic controller mainly involves three steps, namely fuzzification, fuzzy rule base and defuzzfication which is shown in Fig.4. Fuzzification is a process in which the inputs are fuzzified between a range of 0 to 1. Rule base is formed by the experts knowledge and depending on the inputs, the rule base generates the corresponding linguistic variable output. This output is defuzzified from 0 to 1 to a global value. The designed FLC has two inputs,

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error (*e*) and rate of change of error (*ce*) and a controller output (*du*). The number of necessary fuzzy sets and their ranges are designed based upon the experience gained on the process. A Mamdani based system architecture has been realized. Max-min composition technique for the inference engine and center of gravity method for defuzzification have been used. In the present work, seven triangular fuzzy sets are chosen as shown in Fig. 5 and are defined by the following library of fuzzy set values for the error *e*, change in error *ce* and for the change in duty cycle *du*. NB: Negative Big, NM: Negative Medium, NS: Negative Small, Z: Zero, PS: Positive Small, PM: Positive Medium, PB: Positive Big. The fuzzy rule base consists of 49 rules which are used to produce change in duty cycle (du) of the MOSFET of the Luo converter.

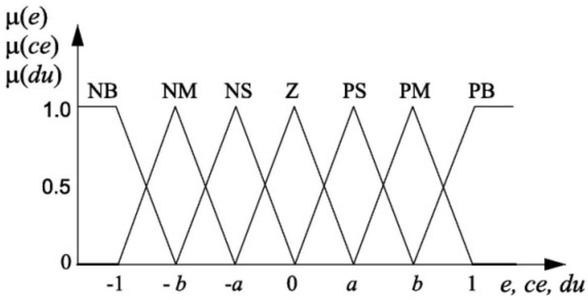

Fig. 5 Triangular Type Membership Functions for Error, Change in Error and Change in Duty Cycle

The derivation of the fuzzy control rules is heuristic in nature and is shown in Table 1. The inference mechanism seeks to determine which rules fire to find out which rules are relevant to the current situation. The inference mechanism combines the recommendations of all the rules to come up with a single conclusion.

Table 1 Rules for Mamdani-Type Fuzzy System

e \ *ce*	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

Since the inferred output is a linguistic value, a defuzzification operation is performed to obtain a crisp value. In this work, the centre of gravity or centroid method is used for de-fuzzification. As a result the control increment is obtained by the eqn. 2.

$$du = \frac{\sum_{i=1}^{m} d_i A\,(\mu_i)}{\sum_{i=1}^{m} A\,(\mu_i)} \qquad (2)$$

Here d_i is the distance between i^{th} fuzzy set and the centre. $A\,(\mu_i)$ is area value of i^{th} fuzzy set.

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IV. BACTERIAL FORAGING OPTIMIZATION ALGORITHM (BFOA)

Many of species depends in its survival on their fitness. The law of evolution supports those species who have better food searching ability and either eliminates or reshapes those with poor search ability. Application of group foraging strategy of a swarm of *E.coli* bacteria in multi-optimal function optimization is the notion of the new algorithm. So by understanding and modeling of foraging behavior in any of the evolutionary species, leads to its application in any nonlinear system optimization algorithm. The foraging strategy of Escherichia coli bacteria present in human can be described by four processes, namely chemotaxis, swarming, reproduction and elimination-dispersal.

Chemotaxis

The behavior of the bacteria toward the nutrient sources is interpreted as chemotaxis. The bacterium tries to find nutrient-rich areas and stay away from toxic environments. An E.coli bacterium moves in 2 different ways: tumble and swim. Tumble is a unit walk in a random direction and is always continued by another tumble or aswim. If a random direction results in a better position, it will be followed by swim, or else another tumble will be taken. In fact, swim is a unit walk in a previous random direction. In each tumble unit, the walk position of the bacterium is updated based on Eqn. 3.

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\phi(j) \tag{3}$$

where i is the index of the bacterium, and $\theta^i(j,k,l)$ is the position of the i^{th} bacterium in the j^{th} step of chemotaxis, the k^{th} stage of reproduction, and the l^{th} stage of elimination-dispersal. C is the step size of the chemotaxis operation, which determines the height of each random step. The cost function of the i^{th} bacterium is determined based on its position and is represented by $J(i,j,k,l)$.J_{min} is represented by the minimum fitness value. In the swim stage, if at $\theta^i(j+1,k,l)$ the cost function becomes better than at $\theta^i(j,k,l)$, another step will be taken in the same direction. This sequence will continue until N_s steps are taken in swim. N_s is the upper band for the number of steps in swim.

The above discussion is specified to the single bacterium. Each bacterium has repellant and attractant effects on the others. To consider these effects, Eqn. 4 is added to the cost function.

$$J_{cc}(\theta, P(j,k,l)) = \sum_{i=1}^{S} J_{cc}\left(\theta, \theta^i(j,k,l)\right) = \sum_{i=1}^{S}\left[-d_{attractant}\exp\left(-w_{attractant}\sum_{m=1}^{p}(\theta_m - \theta_m^i)^2\right)\right] + \sum_{i=1}^{S}\left[h_{repellant}exp\left(-w_{repellant}\sum_{m=1}^{p}(\theta_m - \theta_m^i)^2\right)\right] \tag{4}$$

$$J = J(i,j,k,l) + J_{cc}(\theta, P) \tag{5}$$

Where $\theta^i = [\theta_1, \cdots, \theta_p]^T$ is the position of the i^{th} bacterium in a p-dimensional space, $\theta_m^i$is the m^{th} component of position $\theta^i$for the i^{th} bacterium, S is the number of bacteria (population size), $d_{attractant}$ is the depth of the attractant released by the cell, $w_{attractant}$ is a measure of the width of the attractant signal, $h_{repellant}$ is the height of the repellant effect, and $w_{repellant}$ is the measure of the width of the repellant.

Reproduction

The basic idea of this operation is that nature tends to eliminate animals with poor foraging strategies and keep those that have better ones. In this operation, the whole population is sorted based on fitness. Eqn. 6 shows how the fitness functions are sorted. Half of the population, which has the worse cost function, is eliminated. Each of the remaining members, which have better fitness, is reproduced to two children bacteria to keep the population size constant. N_{re} is the number of reproduction steps that should be taken.

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$$j^{i}_{health} = \sum_{j}^{N_c+1} J(i,j,k,l) \tag{6}$$

Elimination and dispersal

To increase the ability of bacteria for global searching and to prevent them from becoming involved in local optimums, some of the bacteria are randomly eliminated and some of them are dispersed. $N_{ed}$is the number of elimination and dispersal steps that should be taken.

V. OPTIMIZATION OF FLC USING BFOA

In this research work, MFs of input/output variables, rule base and input/output scaling factors of FLCs are determined with BFO algorithm. The method of tuning fuzzy parameters is based upon minimizing the ISE.

The BFOA has been programed using MATLAB M-file to calculate the optimal parameters of fuzzy controller then connected with system simulink. The controller tuning process is employed to find the best possible values for fuzzy parameters. In order to achieve the superior accuracy during the optimization search, it is necessary to assign appropriate fuzzy values which guides the BFO algorithm. The performance criterion with five parameters, such as ISE, IAE, % peak overshoot, settling time and rise time are considered in this work. Table 2 list out the circuit parameters of POELC. Table 3 lists the parameters of BFOA used in this work.

Table 2 Circuit Parameters for POELC

Parameters	**Values**
Inductors (L_1& L_2)	100 μH
Capacitors (C & C_0)	5 μF
Load resistance (R)	10Ω
Input Voltage (V_I)	10V
Output Voltage (V_O)	20V
Switching frequency (f_s)	50KHz
Range of duty ratio (*d*)	0.1-0.9
MOSFET	IRF250N
Diode	UF5042

Table 3 Parameters of Bacterial Foraging Optimization Algorithm

Parameter	Value	Parameter	Value
S	10	C(i)	0.1
p	58	P_{ed}	0.25
N_s	4	$d_{attractant}$	0.4
N_c	5	$w_{attractant}$	0.4
N_{re}	4	$h_{repellant}$	0.5
N_{ed}	3	$w_{repellant}$	0.5

VI. SIMULATION RESULTS AND DISCUSSION

MATLAB model of the Luo converter is simulated for different types of disturbances and results are obtained. The simulation was run under MAT LAB with Fuzzy logic toolbox. The merit of these controls algorithm is that they

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eliminate the steady state output voltage error. The steady state output voltage is always maintained at 20 V. Fig 6. Shows the step responses of Luo converter with Fuzzy and BFOA-fuzzy controllers

Fig. 7 shows the responses of Luo converter with controllers under line disturbances of ± 25%. When the input voltage increases from 10 V to 12.5 V, the settling time is 3.63 msec and % peak overshoot is 35.45 for fuzzy controller and the settling time is 1.12 msec and % peak overshoot is 5.5 for BFOA based FLC. When the input voltage is decreased from 12.5 V to 10 V, the output voltage is settled at 4 msec with peak overshot of 30.75% for FLC and the output voltage is settled at 0.88 msec with peak overshoot of 6.59% for BFOA-FLC. When the system is subjected to a sudden change in load (20% increase), it is being observed that the % peak overshoot is 3.3 and 28.5 and settling time is 0.88 msec and 3.27 msec for BFOA-FLC and FLC respectively which is shown in Fig. 8. Similarly when a change of load is 20% decrease, it is observed that the % peak overshoot is 3 and 27.45 and the settling time is 1.09 msec and 1.45 msec for BFOA-FLC and FLC respectively. The simulation is carried out by varying the system reference voltage where the result for the output voltage is shown in Fig. 9.

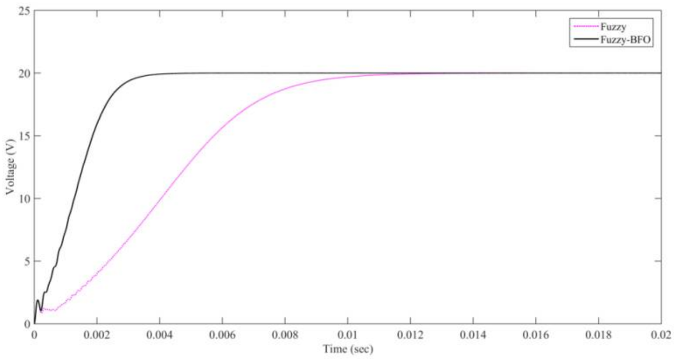

Fig. 6 Step Responses of Luo Converter with Fuzzy and BFOA-fuzzy Controllers

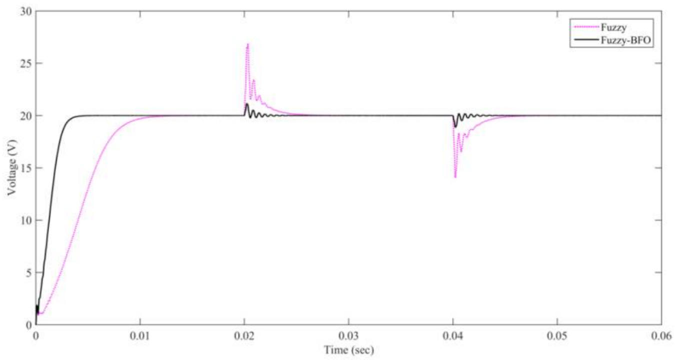

Fig. 7 Responses of Luo Converter for ± 25% Line disturbances

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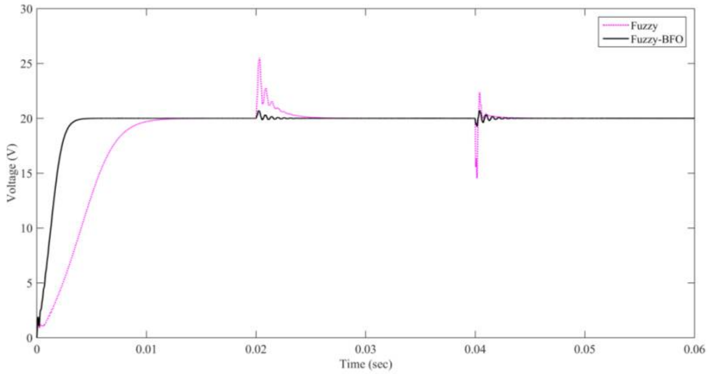

Fig.8 Output Responses under ± 20% Load Disturbances

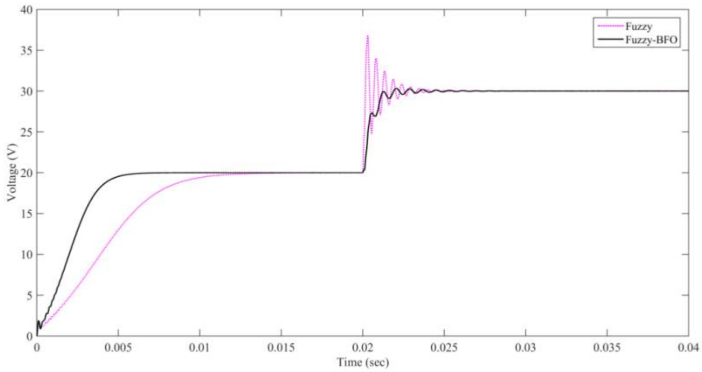

Fig. 9 Servo Responses of Luo Converter with Controllers.

VII. CONCLUSION

Bacterial Foraging Algorithm was successfully utilized to obtain the optimal values of fuzzy parameters. The bacterial foraging algorithm uses bacterial operations to tune the values of fuzzy parameters where the bacterial operations include chemotaxis, swarming, reproduction, elimination and dispersal. BFOA improved the system response of the Luo converter reducing rise time, settling time and peak overshoot, thereby successfully fulfilling the objective of obtaining desirable time domain system responses. From the simulation results it is seen that, even when subjected to line and load disturbances, output voltage reached steady state within a time duration of 1.12 milliseconds exhibiting stability and an ability to withstand the disturbances.

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