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Improvement of Performance and Quality of Power Using Solid Oxide Fuel Cell-A Review

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***Abstract*— In this manuscript, a grid-connected Solid Oxide Fuel Cell (S OFC) system has been considered. SOFC has numerous benefits in comparison to other available Fuel Cell s (FCs) as it possesses longer stability, flexibility in fuel use, negligible harmful emissions, excellent dynamic characteristics, and comparatively very less cost. Conventional PID controller being a nonlinear controller fails to potentially respond to the nonlinearities of a power system network. Intending to dynamically tune the PID controller parameter a robust Crow Search (CS) based evolutionary technique has been suggested in this paper. The system is developed in the MATLAB/Simulink architecture and the efficiency of the proposed control approach isverifiedbyaddingittoanonlinearloadforsometimeinterval. To confirm power quality enhancement stability analysis through Total Harmonics Distortion (THD) has been carried and the value obtained for the technique suggested is well within the IEEE range. Further, a comparative study of SOFC with classical PID and Crow Search tuned PID has been done considering various characteristics such as SOFC voltage, SOFC active power, SOFC reactive power, grid voltage and grid current.**

***Keywords*— Solid Oxide Fuel Cell (SOFC), Crow Search (CS), Boost Converter (BC), PID controller, Total Harmonic Distortion(THD).**

INTRODUCTION

Thefasterrateoffossilfuelderogationandpollutiondueto its intake is dragging the environment towards unhealthy situations. This in turn influences public health, so to maintain hygiene andbetterpublichealthmorediligenceisgivenforthe addition of sustainable renewable energy production. Solid oxide fuel cell (SOFC) is an alternative solution to the above issues in giving clean automation to an electrochemically produced energy at a larger efficiency. Fuel Cell (FC) is an electric energy device which develops electric energy through fuel and oxidant chemical reaction [1]. The fuel cell does not affect the environment and public health as it offers clean and pollution-free energy with enhanced efficiency. SOFC can be considered as an ideal energy source. It is cast-off in abroad locality or area [2]. SOFC has numerous benefits like high efficiency, more stable, flexible in fuel use, less costly, and applicable for transmission line (which is more than 250) [3-4]. It can also work in high current density. However, SOFC also has some crucial drawbacks like, it works at very high temperatures that finally degrades its performance and thus enhances the cost of material used [5]. So suitable control should be designed to counteract the issues faced.

PID is a conventional controller and is very easy to construct [6]. It also gives an instant response. This conventional controller has three main methods like, ‘P’ (proportional), ‘I’ (integrator), and ‘D’ (derivative). In the ‘P’ methodifthestabilityimprovesthentheaccuracydecreaseand viceversa.Inthis methodcontroller,thesteady-stateerrorcan be decreased but cannot become zero hence ‘P’ controller alone is not used [7]. In ‘I’ method stability is sluggish due to which control system becomes slow. ‘I’ controller decreases steady-state error but it simultaneously decreases stability as well. Hence integral controller alone is not used [8]. In ‘D’ mode system is anticipative due to which controller system becomesfaster.‘D’controllerincreasesthestabilitybutsteady-state error also increases. Hence derivative controller alone is not used [9]. So the simultaneous use of the PID controller is more preferable. Nevertheless, the crucial drawback is it fails to respond dynamically to nonlinearities occurring in an electrical gridnetwork.

Fordynamically tuningthePIDcontrollerparametersmany researchers have suggested many algorithms in the literature like Genetic Algorithm(GA) [10], Particle Swarm Optimization (PSO) [11], Harmonic Search (HS) [12], Bat Algorithm (BA) [13], Group Search Optimizer (GSO) [14], Firefly Algorithm (FA) [15], Brain Storm Optimization (BSO) [16], Ant Colony Optimization Algorithm (ACO)[17], Bacterial Foraging Optimization Algorithm (BFO) [18], and Collective Decision Optimization Algorithm (CDOA) [19]etc. However, among all of them, Crow Search (CS) Algorithm has comparatively more advantages because it is a flight base technique that uses less iteration so computational time is reduced and the execution will be faster[20].

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ThispaperrepresentsaSOFCbasedgrid-connectedpower network in the MATLAB/Simulink environment. For testing the proposed algorithm a nonlinear load fault is added to the system for time t = 0 sec 0.2 sec. From the graphs acquired it can be noticed that the conventional PID controller fails to respond to the nonlinearity and the system goes to instability during the fault time. For the dynamic operation of the PID controller parameters, an evolutionary technique known as Crow Search (CS) algorithm is being adopted in this paper. The CS tuned PID improves the transient stability, mitigate harmonics, and brings back the system to a stable state very fast as compared to the classical PID controller. The Total Harmonic Distortion (THD) calculation has been carried out for verifying the stability indices and the values obtained for the suggested controller is as perIEEE constraint.

The entire paper has been arranged in the following manner. In Section II, the total modelling of the system configuration is discussed. The conventional and proposed control approach is broadly highlighted in Section III. In section IV the MATLAB/Simulink architecture is depicted and the results are analyzed. Lastly in Section V the total paper work is concluded. The values of the parameters used in this study are given in the appendix after the conclusion.

MATHEMATICAL MODELLING

2.1 Modelling of Solid Oxide Fuel Cell(SOFC)

Fuel Cell (FC) is a renewable energy source. FC is a device which develops electric energy through chemical reaction between a fuel and oxidant. At present time Fuel Cell (FC)are 5 types as Proton exchange membrane fuel cell (PEMFC), Solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC), and Phosphoric acid fuel cell (PAFC) and Alkaline fuel cell (AFC). But, SOFC is more beneficial in comparison to other FC's because of [21]: i) it can work in high temperature, ii) its gives high efficiency, iii) is more stableand is suitable for long transmission line [22]. Fig-1 indicates basic circuit of SOFC which is the combination of non-dependent voltage source 'e', dependent voltage source $fe_o(i,t)$, resistor ' r_1', 'r_2', ' r_3' and capacitor 'c_1'.

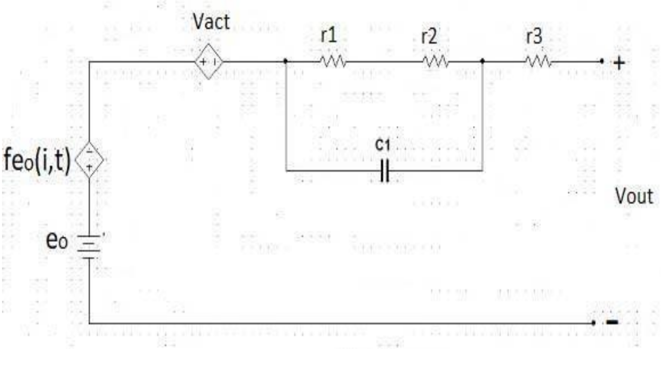


Fig.1. Basic circuit of SOFC

$V_{out}$for this circuit can be written as follows:

$$V_{out} = e - V_{ac} - V_c - V_{\Omega}$$

Where, is output voltage, $'e'$denote open circuit voltage, is voltage across 'r_1' is voltage across 'r_2' and is $'V_{\Omega}'$voltage across 'r_3'resistor.

In this case 'e' can be denoted as given in the equation below

$$e = N_0[e_0 + \frac{r*t}{2*f} * \ln(\frac{PH_2}{PH_0} * (PO_2)^{0.5})] \qquad ()$$

Here, is turnaround voltage, 'r' is general gasoline constant, 't' is heat. and are mole fraction and 'f' value is $9.648*10^4$which faraday constant is.

Also, here flow of electron can be expressed in equation (3) as follows

$$V_{\Omega} = i_0 * r \qquad ()$$

Where, is total current flowing around circuit (Fig.1.)

Equation (4) is used for finding --

$$V_{ac} = -c * \ln(i_0) \qquad ()$$

2.2 Modeling of boostconverter

Boost converter is a switch mode DC-DC converter and basically can be called as a step up chopper. In this chopper output voltage ( ) is more than supply voltage ( ). This chopper is combination of inductor (l), diode (d), switch (Sw) and resistive load as shown in Fig-2. When switch is turned on then inductor stores the energy that's why voltage across the load will be increased [23]. In this case (step up chopper circuit) capacitor used as a backup source which gives supply in the course of switch ' ' time. Here diode create a path for currentinthecourseofswitch' 'time[24].

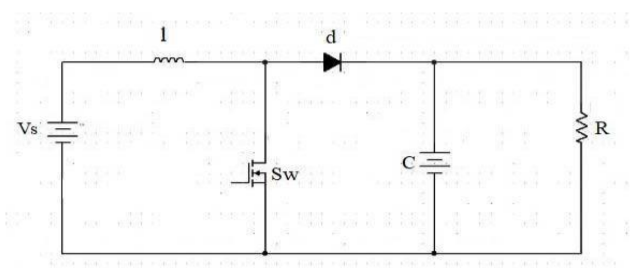


Fig.2. Boost Converter (step up chopper)

The final equation for this chopper can be written as (5)

$$1 - D = \frac{V_{out}}{V_s} \qquad ()$$

Here, 'D' is duty cycle. And D will be mathematically formulated as givenbelow,

$$D = \frac{t_{on}}{t_{on} + t_{off}} \qquad ()$$

And also, for finding critical value of R,

$$R_{crit} = \frac{2*l}{D*(D')^2*T_s} \qquad (7)$$

CONTROLSTRUCTURE

3.1 PIDcontroller

The PID controller is a most common type of linear controller and consists of proportional (P), integration (I), derivative (D) methods. The PID controller consists of three parameters 'Ke', ( )'Ki' and 'Kd'. 'Ke' shows the proportional gainthat decreases the rise time , 'Ki' shows theintegral gain that maintain in decreasing the steady-state error and 'Kd' shows thederivativegainthatdecreasesthepeakovershoot,increase the momentary feedback and it also creates a higherstable system . All of these parameters are interconnected with each other. The PID controller evaluates fault value as the difference within a measure variable and a desire set point. The controller tackle to reduce the errors by fixing the process by the help of a manipulated variable[25-26].

3.2 Crow Search (CS)Algorithm

Crows are assumed to be the most talented in the family of birds. It is said that crows have greater brain with respect to their body size [27]. According to the brain-body proportion, crows have a slightly less brain than humans. There are numerous facts that support the intelligence of the crows. Crows have shown self-consciousness in tests like mirror tests and few tool-fabrication skills [28]. They have good face remembrance ability and safety sense. In addition, they also use tools, communicate in a better way and remember and call where they have hidden their food up to many months' interval of time.

Crows are known to sit, watch and monitor the food being hidden by other birds and as soon as the other bird or the owner leaves they try to capture the food. As a part of stealing, they are conscious enough to be preventive in shifting of hiding places so as to avert of being caught. Although, crows uses their first-hand experience of being a robber and assume themselves the behavior of burglars and decide the safest escape route.

3.2.1 Comparison of CS Algorithm with othertechniques

Techniques like Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Harmony Search (HS) usually use populations for finding the best search position as it enhances the possibility of getting a good solution and an escape from issues of local optima's. Setting of parameters is one of the major disadvantage of evolutionary techniques as it consumes a large amount of time. Algorithms can be easily adopted with less number of adjustment parameters. GA has 6 variables to be adjusted. But Crow Search algorithm being a non-greedy method enhances viciousness of the solutions that are generated. Further it has advantages of tracking and rememberingthebestsolutions.Thismeansateveryrepetition of Crow Search Algorithm, the perfect locations achieved are utilized in finding improved solutions. This concept of Crow search Algorithm makes it far more superior in comparison to other availabletechniques.

3.2.2 Theory of CSAlgorithm

In this article, which is based on intellect behavior, a population based meta-heuristic algorithm, CS, is tried to be developed. The core principles can be demonstrated as cited below [29]:

- Crows prefer to be inteam
- They have a sharp memory to remember their food hidingplaces.
- They observe and learn from each other the acts of thievery
- Crows can assume and plan their escaperoute.

It has been presumed that there is a d - dimensional surrounding that includes the total crows. The total crows (group_size) z and location of the crow p on a time (iteration)

itr at the search space is representedbyvector $x^{p,itr}$ (p=1,2,3,…..,z)(itr=1,2,3,….,   )   where   = $[x_1^{p,itr}, x_2^{p,itr}$,…..,   ]   and   accounts as the maximum iterations. Every crow has a recognition which recognizes the location of their hiding places. At theiteration

itr,thehidingcrowislocatedandisshown by   .Itseems to be the best position that has been obtained by the crow p so far. Thus the location of the best experienced is being memorized by every crow. Crows then locomote in the surrounding and for searching better food sources.

Presume that on iteration , crow $'itr'$ marked q wishes to visit

at its hiding place,   .During this iteration, crow p follows crow q to approach the latter's hiding place. Therefore two cases may happen[30-33]:

Case1: Crow q is unknown of the fact that crow p is following. Thus crow p will reach q's hiding place. Therefore the new position ofcrow p is obtained accordingly: NJ

= + (-) (8)

Where is random number which has uniform distribution

between 0 & 1 &   stand for length of flight, crow p on iteration   .

Fig. 3 depicts the simplified representation of the case. Minute values of fl directs to the local search in vicinity of   and large values would result in general search (distant from).

Case 2: Crow q is aware that crow p is following. Therefore to safeguard its cache from being stolen, crow q would fool by travelling to another position.

Totally, both the cases can be expressed as:

={ + (−)a randomposition
= otherwise (9) Where is

random number which has uniformdistribution

between0&1&   showstheprobabilityofawareness of crow q at iterationitr.

Met heuristic techniques should offer a well stability among intensification and diversification. In Crow Search Algorithm, Awareness Probability (AP) parameter is an important factor. Thus by using the values of AP which are small, starts increasing intensification and Crow Search Algorithm tends in exploring the search place on a global size. Finally it is concluded that, huge values of Awareness Probability AP) increase diversification.

3.3.3 Crow Search Algorithm Execution forOptimization

presume the problem and flexible parameters

The development problem, decision variables and constraints are explained. Then, the flexible parameters of Crow Search Algorithm (of flock size (z)), (Maximum number of iterations (

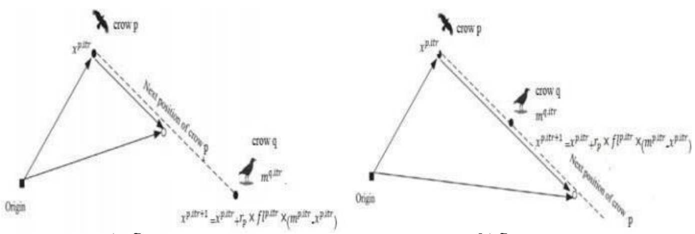
)). Flight length and awareness probability (AP) are evaluated.

Compute the location and memory

N number of crows are arbitrarily located in a 'd' dimension search space. Every crow shows a best possible solution to the issue.

$$\text{Crows}=\begin{bmatrix} x_1^1 & x_2^1 & x_d^1 \\ \dots & \dots & \dots \\ x_1^n & x_2^n & x_d^n \end{bmatrix} \quad (10)$$

The memories of every crow is presumed. As initially the crows were inexperienced, it has been presumed that crows hides its foods at their initial positions.



a) fl<1 b)fl>1

Fig. 3. Flow chart of CSA algorithm

IV. MATLAB/SIMULATIONMODELANDANALYSISOFRESULTS

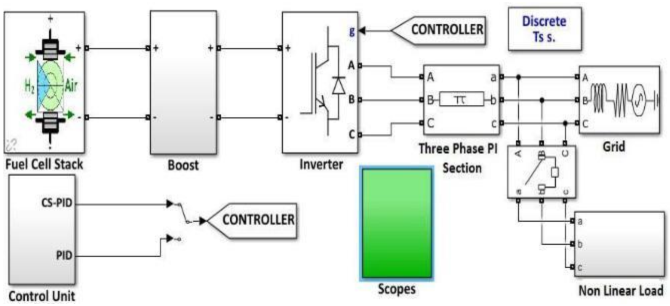


Fig.4 MATLAB/Simulink Model of the system undertaken for study

In this work, a SOFC is considered for study along with boost converter, three phase voltage source inverter and controllers in a grid tied mode. Various characteristics such as SOFC voltage, SOFC active power, SOFC reactive power, grid voltageandgridcurrentarefoundoutandacomparativestudy between the classical PID controller and the proposed CS tuned PID controller has been studied. To evaluate the performance of SOFC with suggested technique the system has been subjected to a nonlinear load, from time t=0 sec to 0.4 sec. The result obtained clearly defends thenovelty, functionality and robustness of the proposed technique as compared to the conventional PID technique.

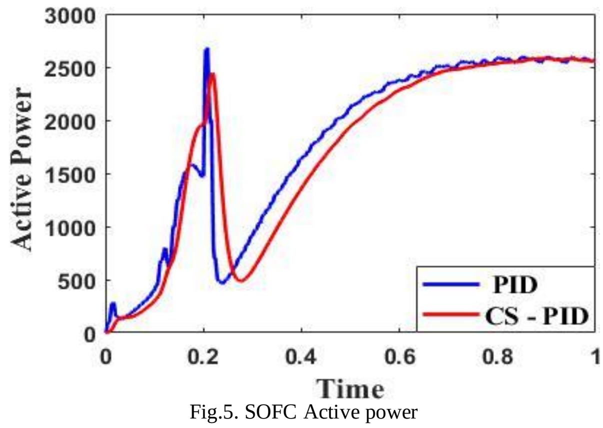


Fig.5. SOFC Active power

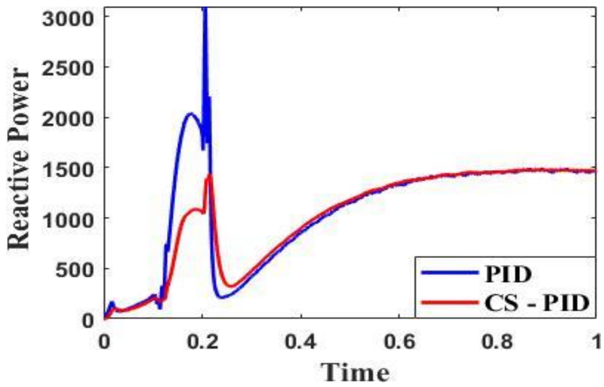


Fig.6. SOFC Reactive power

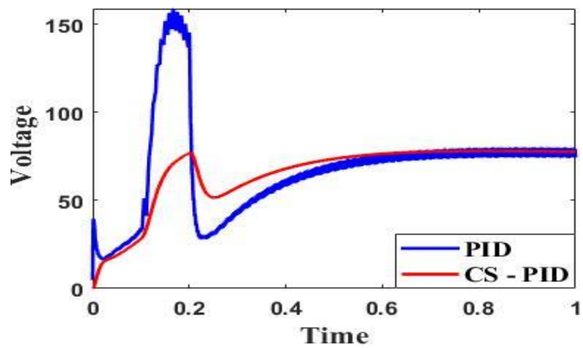


Fig.7. SOFC voltage

Fig.5, 6 and 7 indicates the output voltage, active power and reactive power of SOFC. From these figures it can be concluded that the CS technique bring the system to state faster with reduced rise and peak time. Further it can be seen that the harmonic content has been reduced to a greater extent due to the proposed technique.

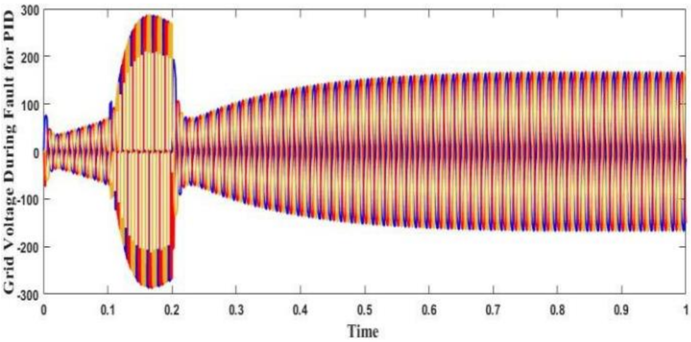


Fig.8. Grid voltage during fault forPID

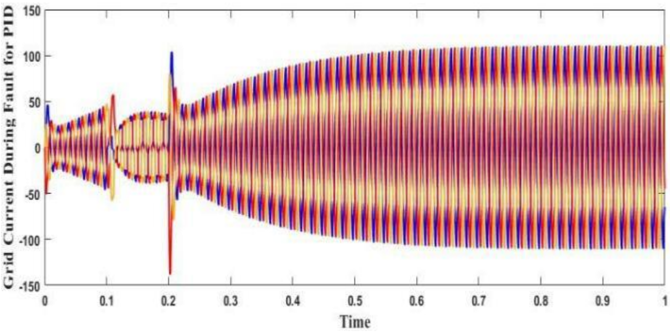


Fig.9. Grid current during fault forPID

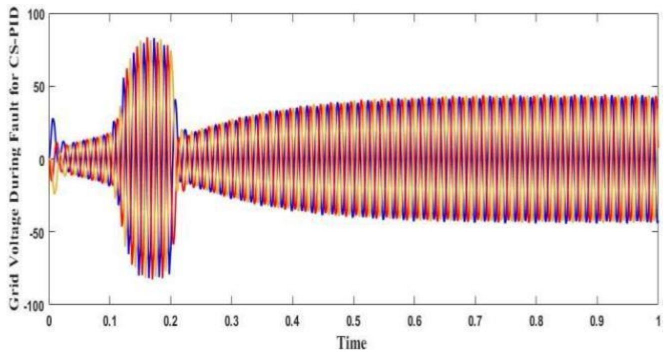


Fig.10. GridvoltageduringfaultwithCSoptimizedPID

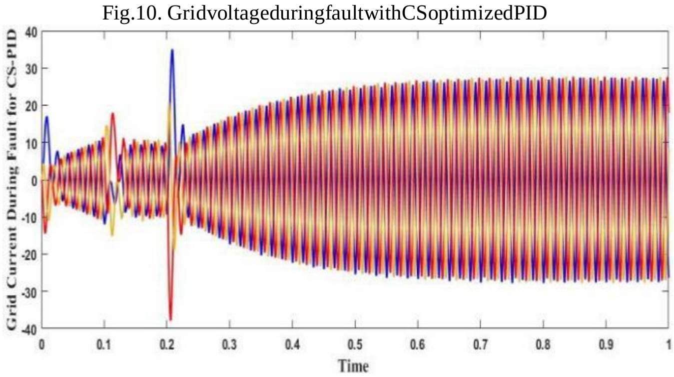


Fig.11. Grid current during fault with CS optimizedPID

Fig.8, 9, 10 and 11 indicates the grid voltage and grid current during fault time for PID and CS optimized PID respectively. The above figures indicates that the harmonics content are more for PID and comparatively less for the proposed method. Also the system is comparatively more stable with less rise and peak time for the CS optimized PID controller.

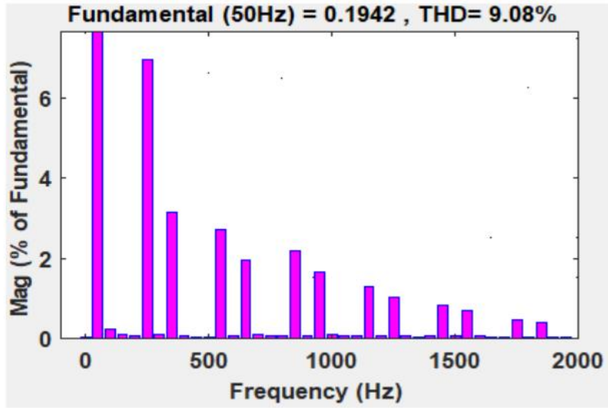


Fig.12. THD of Grid voltage with PID

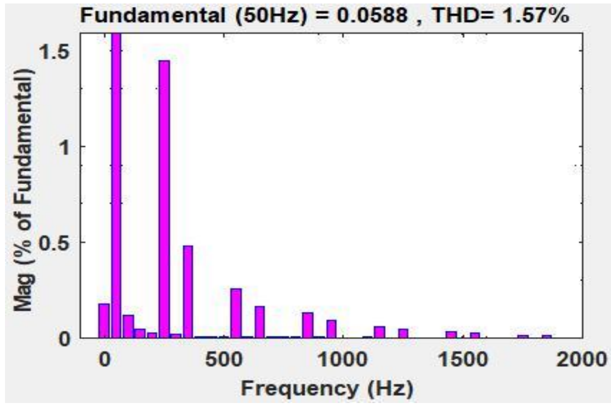


Fig.13. THD of grid voltage with CS-PID

Fig.11 and 12 indicates the THD values of the grid voltage during fault for PID and CS optimized PID for verifying the stability indices as per IEEE constraints. The calculated THD values are 9.08% and 1.57 % for PID and proposed CS-PID respectively which indicates that the suggested algorithm is more efficient in comparison to other controller in terms of transient stability enhancement.

CONCLUSION

In this paper, a Crow Search (CS) Algorithm based on the crow's clever conduct is proposed for dynamically tuning the PID controller parameters to robustly respond to any nonlinearities in the power grid network. Comparative studies has been made between the conventional PID controller and the Crow Search optimized PID controller considering various characteristics such as SOFC voltage, SOFC active and reactive power, grid voltage and grid current. Simulation performance proves that suggested algorithm is more efficient in reducing the steady state error, enhancing the transient stability, reducing peak overshoot and restoring system to stable state as soon as possible on the occurrence of the fault. Also from the output results it can be concluded that the concurrence rate of Crow Search method is better than other available techniques. The THD values found out are well within IEEE limits just justifying its real time application.

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Appendix

Parameters	Values
SOFC	Vo=40, E=45, R1+R2=0.4Ω, R3=0.06 and C=0.25F
Boost	L= 0.8mH, C=100 µF, Fs=30KHz, V0=100 and Vin=40V
Nonlinear Load	Nominal frequency-50Hz, power-2500W
Grid	V=100, X/R=7, f=50Hz

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