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Improve power quality of charging station unit using African vulture optimization algorithm

Saleh Masoud Abdallah Altbawi[1], Saifulnizam Abdul Khalid[1], Ahmad Safawi Mokhtar[1], Rayan Hamza Alsisi[2], Zeeshan Ahmad Arfeen[3], Hussain Shareef[4], Mehreen Kausar Azam[5]
[1]Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor Bahru, Malaysia
[2]Department of Electrical Engineering, Faculty of Engineering, Islamic University of Madinah, Madinah, Saudi Arabia
[3]Department of Electrical Engineering, The Islamia University of Bahawalpur, Bahawalpur, Pakistan
[4]Department of Electrical Engineering, United Arab Emirates University, Al Ain, United Arab Emirates
[5]College of Engineering and Sciences, Institute of Business Management Sindh, Karachi, Pakistan

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ABSTRACT

In recent years, there is growth in acceptance to consume fewer fossil fuels globally and the manufacturing of electric vehicles (EVs) has become more popular. However, the increase in the number of systems connected to the grid that contain EVs with a huge power capacity leads to unstable working in the power system. To assess the stability of the electric charging station several control approaches in AC part and DC parts during charging mode and discharging modes are tested. African vulture optimization algorithm (AVOA) has been utilized to tune the system controllers (proportional integral-derivative (PID)/tilt-integral-derivative (TID) controllers). The superiority of AVOA is confirmed by comparing the performance with the genetic algorithm (GA). Two objective functions have been used i.e. integral time absolute error (ITAE) and integral square time error (ISTE). AVOA-tuned TID controllers using ISTE were found to be the best to contain the frequency deviations. The results have shown of the AC part and DC part is within an acceptable limit recommended by IEEE standard. Further, maximum peak overshoot, undershoot, and settle time obtained by AVOA-tuned PID and TID controllers are found the best. Finally, the improvement of the performance index obtained by AVOA over its counterpart GA is confirmed.

Corresponding Author:

Saleh Masoud Abdallah Altbawi
Faculty of Electrical Engineering, Universiti Teknologi Malaysia
81310 Johor Bahru, Johor, Malaysia
Email: masoud@graduate.utm.my

1. INTRODUCTION

Electric vehicles (EVs) rely on an electrical power source to charge their batteries. As a result, the use of EVs leads to an increase in power demand across the entire electrical system [1]. Specifically, long-distance travel and high-performance charging stations pose challenges for control units and managing instantaneous demand. The storage system in EVs has several limitations, such as long charging times, high costs, installation costs, material composition, proper disposal, sizing, safety procedures, the need for refueling stations, and limited power capacity. Furthermore, recent EVs charging stations that operate in both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) modes have limitations such as a high level of harmonics in the input current, and absorption of reactive power from the grid, which leads to a decrease in power factor [2]. To solve these issues, there are several solutions, and the most important is to underpin the control of bidirectional DC/DC converters. The output voltage of a bidirectional DC/DC converter needs to preserve optimality and robustness by utilizing a proper control ability under the effect of load changes and input-voltage disturbances. That leads to many issues required to address by researchers and engineers. One of the most widely used model-free voltage-regulation schemes is to use different kinds of proportional integral derivative (PID) controllers [3]. Therefore, adjusting the parameters of the controller for different working situations, will lead to acceptable execution in these situations [4]. Hence, in many studies, different kinds of artificial intelligence (AI) like metahuristic algorithms have been utilized to adjust the parameters of the controllers [5].

Metaheuristic algorithms are general optimization methods that can be utilized to solve a wide range of problems [6]. They are not tailored to a specific problem but rather provide a general strategy for addressing optimization challenges [7]. These algorithms are commonly used to find approximate solutions to complicated or unsolvable optimization problems for which no precise method exists. Some well-known metaheuristic algorithms include genetic algorithms (GA), simulated annealing, particle swarm optimization, quantum-inspired metaheuristic algorithm [8], sparrow search algorithm [9], chaotic vortex search algorithm [10], multi-objective optimization algorithm [11], improved gradient-based algorithm [12], and spotted hyena optimizer [13]. These algorithms are based on natural phenomena and mimic the behavior of natural systems in order to find the best solutions to problems [14].

Here some recent articles have used AI to address the issues in EV charging stations. Yong *et al*. [15] presented a model of a bi-directional EV charger with reactive power compensation. Albeit, the work does not provide a simulation of discharging mode and its effects on power compensation. Smart charging with the V2G and G2V using model predictive control (MPC) [16], and direct model reference adaptive control (DMRAC) algorithm has developed [17]. Although, the sensitivity of the controller in both methods is slow which increase the time response to overcome the changes during the operation. GA has been utilized to support static frequency sliding regulators for quadratic boost converters in fuel cell vehicle. However, the GA falls in local optima and does not guarantee the best operation [18].

As the African vulture optimization algorithm (AVOA), has advanced level among recent metaheuristic algorithms used in solving many electrical real-world problems. AVOA algorithm has used to tune proportional–integral (PI)-based maximum power point tracking (MPPT) controller for hybrid renewable energy sources (RESs) of solar photovoltaic (PV) and wind systems, to smooth the output fluctuations [19]. Belmadani *et al*. [20] improved AVOA (IAVOA) which incorporates a twofold strategy, used to extract characteristics for the double/triple PV Diode models based on the root mean square error (RMSE). Salah *et al*. [21], AVOA algorithm has been used to adjust the PI controller during discharge conditions in a small DC circuit. Even though, this system is not suitable for big capacity systems, and does not give a solution for the AC section.

This article aims to design an optimal control strategy for a bidirectional DC/DC converter using AVOA-based tilt-integral-derivative (TID) controller. The error signal is calculated directly using the different error signals (integral time absolute error (ITAE) and integral square time error (ISTE)). The rest of the article contains, components of the charging station, control of the rectifier, control of bidirectional converter, GA, and AVOA. Finally, the results and discussion ended with the concluding remarks. The major contributions of this article are: i) building charging station with interlink of DC and AC sections to enhance the performance; ii) propose two efficient control strategies that supervise DC voltage, and AC voltage to regulate both sides of the network during different aspects; and iii) tuning of the proposed control method using the AVOA along with two well-known objective functions.

2. COMPONENTS OF THE CHARGING STATION

The typical configuration of a high-performance charging station consists of an AC/DC rectifier and a directional DC/DC converter [22]. In the charging mode, the station rectifies the input of the three-phase AC supply provided by the grid into the DC output. A bidirectional DC/DC converter is then used to adjust the DC output level to support the batteries of the EVs. However, in discharging mode, the process will be the opposite way starting from the batteries of EVs, which inject the power into the grid [23]. The control topology of AC/DC part of the system is the saddle point by controlling the demand flow in both ways between the utility grid and the electric charging station and vice versa. Figure 1 describes the main components of the charging station.

2.1. Control of bidirectional converter

One of the most popular non-linear control techniques is sliding mode because of its quick dynamic response, resistance to parameter fluctuations, and low susceptibility to outside disturbances. Whereas, the proposed sliding mode technique tracked the current of battery charging reference (I_{BC-ref}). The difference between the charging current reference and measured charging current is handled and the response going to (PID/TID) controller [24]. The output of the controller is injected into DC PWM generator which injects pulses to the bidirectional converter to operate [25].

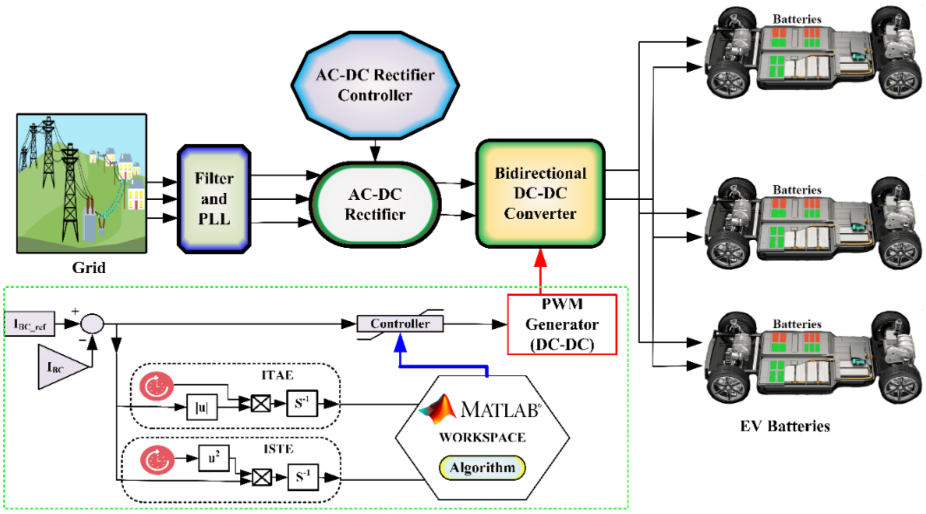


Figure 1. Main components of the charging station

2.2. Integral time absolute error

Owing to the smoother flow and steady outcomes, integral time absolute error (ITAE) has opted as the cost function (CF) in many studies. Whereas, ITAE is generally used as performance criteria in stability analysis. In this study, ITAE can be expressed as:

$$ITAE = \int_0^\infty t\,|e(t)|dt \tag{1}$$

2.3. Integral square time error

The most significant benefit in the system performance using ISTE that it can simply be evaluated analytically using the s-domain formulation which is not the case for ITAE criteria. ISTE could have a negative value which improves changes tracking and disturbance rejection ability. The mathematical representation of ISTE can be formulated as (2):

$$ISTE = \int_0^\infty t^2 e(t)dt \tag{2}$$

2.4. Genetic algorithm

The GA is a metaheuristic method that is based on Darwin's theory of biological evolution. The core principle of GA is the survival of the fittest, where the best genes are passed on to the next generation [26]. This concept helps species adapt better to the environment, such as finding food and avoiding predators. In each generation, the genetic mechanism is applied through main genetic factors to select the best individuals from the current population of the generation [27].

2.5. African vulture optimization algorithm

A novel nature-inspired metaheuristic algorithm inspired by African vultures' routine that mimics African vultures' foraging and navigation behaviours to find food [28]. The AVOA was formulated in 4 separate steps:

a. Defintion of the best vultures

It refers to the process to define the optimal vulture of the first set and the second-best answer-as well as the best vulture of the second set, and the other answers using the given (3):

$$R(i) = \begin{Bmatrix} best\ vulture_1 if\ p_i = L_1 \\ best\ vulture_2 if\ p_i = L_2 \end{Bmatrix} \tag{3}$$

b. Rate of starvation of vultures

To model the rate of being satiated is represented in (4) and (5):

$$t = h \times (sin^{w}\left(\frac{\pi}{2} \times \frac{iteration_i}{max.iterations}\right) + \cos\left(\frac{\pi}{2} \times \frac{iteration_i}{max.iterations}\right) - 1) \quad (4)$$

$$F = (2 \times rand_1 + 1) \times z \times \left(1 - \frac{iteration_i}{max.iterations}\right) + t \quad (5)$$

c. Exploration

This process is demonstrated in (6):

$$P(i+1) = \begin{Bmatrix} equation\ (7)\ |\ if\ P_1\ \geq rand_{P_1} \\ equation\ (8)\ |\ if\ P_1\ < rand_{P_1} \end{Bmatrix} \quad (6)$$

$$P(i+1) = R(i) - D(i) \times F \quad (7)$$

where $P(i+1)$ is the vulture position vector in the next generation, $R(i)$ is one of the best vultures. Furthermore, X is where the vultures change his position randomly to maintain the food away from other individuals. $X = 2 \times rand$, where rand is a random value in the interval (0,1).

Exploitation (first stage): this execution of this process is displayed in (8):

$$P(i+1) = \{\ D(i) \times (F_i + rand_4) - d(t) \quad (8)$$

where, $rand_4$ is a random number between 0 and 1, and $d(t)$ is the measured distance between the individual and one of the two sets' best vultures.

d. Exploitation (second stage)

This procedure is calculated in (9):

$$P(i+1) = \begin{Bmatrix} equation\ (10)\ |\ if\ P_1\ \geq rand_{P_2} \\ equation\ (11)\ |\ if\ P_1\ < rand_{P_2} \end{Bmatrix} \quad (9)$$

Therefore, the vulture's position can be updated using (10):

$$P(i+1) = \frac{A_1 + A_2}{2} \quad (10)$$

In (20) and (21) are used to calculate A_1 and A_2, respectively:

$$A_1 = best\ vulture_1(i) - \frac{best\ vulture_1(i) \times P_i}{best\ vulture_1(i) - {P_i}^2} \times F_i \quad (11)$$

$$A_2 = best\ vulture_2(i) - \frac{best\ vulture_2(i) \times P_i}{best\ vulture_2(i) - {P_i}^2} \times F_i \quad (12)$$

Similarly, when the AVOA is in its second stage, the vultures would flock to the best vulture to forage for the remaining food. Therefore, the vultures' position can be updated using (22):

$$P(i+1) = R(i) - |d(t)| \times F_i \times\ Levy(d) \quad (13)$$

Here, d denotes the problem dimensions. The AVOA's effectiveness was improved by utilizing Lévy flight (LF) patterns, which were derived utilizing (14):

$$LF(x) = 0.001\ \times \frac{u \times \sigma}{|v|^{\frac{1}{\rho}}} \quad (14)$$

where:

$$\sigma = \left(\frac{\Gamma(1+\beta) \times sin\left({}^{\pi\beta}/_{2}\right)}{\Gamma(1+2\beta) \times \beta \times 2 \times \left(\frac{\beta-1}{2}\right)}\right)^{\frac{1}{\rho}} \quad (15)$$

where, v and u are arbitrary values between 0 and 1, and β is a constant value of 1.5.

3. RESULTS AND DISCUSSION

In this section, to evaluate the effectiveness of the proposed methods, optimization was performed using the GA and AVOA algorithms. These results were then applied to the PID and TID controllers of the bidirectional DC-DC converter to determine the optimal parameters. The results of optimal parameters of the controllers are summarized in Table 1. In addition, the results of optimal performance of DC bus voltage are summarized in Table 2.

Table 1. Optimal parameters of the controllers

Parameters	GA_PID		GA_TID		AVOA_PID		AVOA_TID	
	ITAE	ISTE	ITAE	ISTE	ITAE	ISTE	ITAE	ISTE
Kp	0.01562	5.98581	194.4854	310.86	150.9917	0.0048	944.77	989.215
Ki	854.6098	762.0675	-3.1356	-6.572	-4.0400	125.103	6.1957	-1.8539
Kd	2.1247	0.448507	4.64969	2.804	2.48558	0.0002	0.0028	0.0491
N	NA	NA	2.5107	1.9674	NA	NA	2.8364	3.1067

Table 2. Optimal performance of DC bus voltage

Approach	Best fitness	Rise time (ms)	Overshoot (%)	Undershoot (%)
GA_PID_ITAE	0.1335	9.9132	1.065	2.677
GA_PID_ISTE	-31.062	9.6547	1.192	2.891
GA_TID_ITAE	0.0761	10.9257	0.992	2.307
GA_TID_ISTE	-35.824	11.8260	1.394	2.268
AVOA_PID_ITAE	0.1501	12.8462	0.966	2.409
AVOA_PID_ISTE	-41.372	12.6073	0.786	2.234
AVOA_TID_ITAE	0.0485	9.2510	0.897	2.317
AVOA_TID_ISTE	-96.985	11.2821	0.758	2.193

When operating in G2V mode, the battery is charged from the grid by utilizing a negative reference current. The voltage and current are out of phase, resulting in negative active power, indicating that power is being transferred from the grid to the battery. To work the system in V2G mode, the charging battery from the grid will be done using positive reference current. Both the voltage and current are aligned in phase and active power, in this case, is positive which means active power is injected to the grid. Figure 2 shows the three-phase grid side voltage and current. Where, the controller recovers the abrupt conditions in just 0.01 seconds during start working at 0 seconds and changing from charging and discharging mode at 0.5 seconds.

The control part of the EV system plays the main role in imaginary power decompensating regulation and DC-link voltage adjustment to address the switches of the AC/DC rectifier as well as the bidirectional DC/DC converter to attain the nominal three-phase voltage support and near to the DC-link voltage reference. The reactive power and DC voltage fluctuation, are reduced substantially which is the main object of the proposed method. The proposed method employs the use of both the controllable rectifier and bidirectional converter to achieve nominal voltage at the utility grid and stable voltage value at fixed DC-link voltage, by utilizing the techniques of recompensing reactive power and DC-link voltage regulation. This method efficiently reduces the mismatch of reactive power among converters.

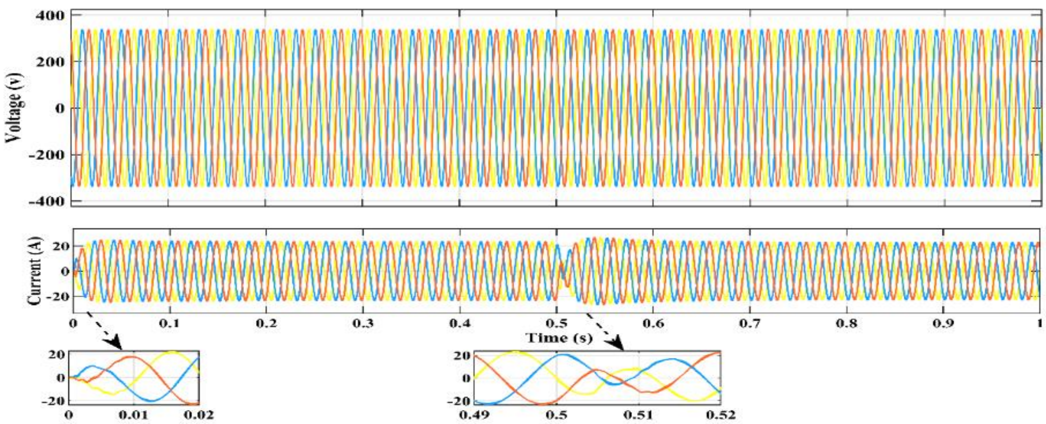


Figure 2. Three-phase grid side voltage and current

Figure 3 shows the voltage at DC bus. As can be seen from the graph, the overshoot and smaller stable time of the average current mode is small in both cases. Moreover, AVOA-TID-ISTE system have simulated waveforms have less oscillations with smoother voltage response. The behavior of the battery current is presented in Figure 4. In the case using AVOA-PID-ISTE, it has less ripples; thus, it reaches the steady-state more rapidly than the AVOA-PID-ISTE.

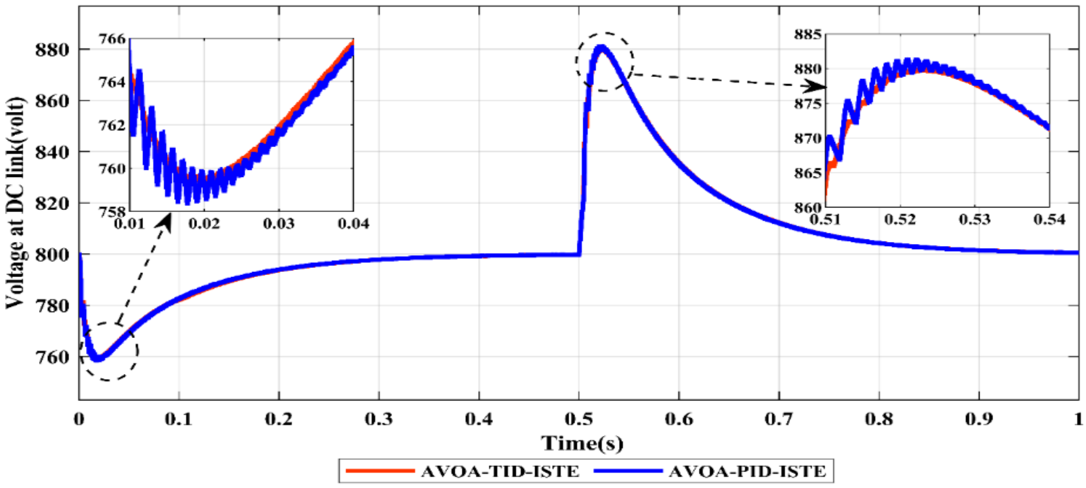


Figure 3. The voltage at DC bus

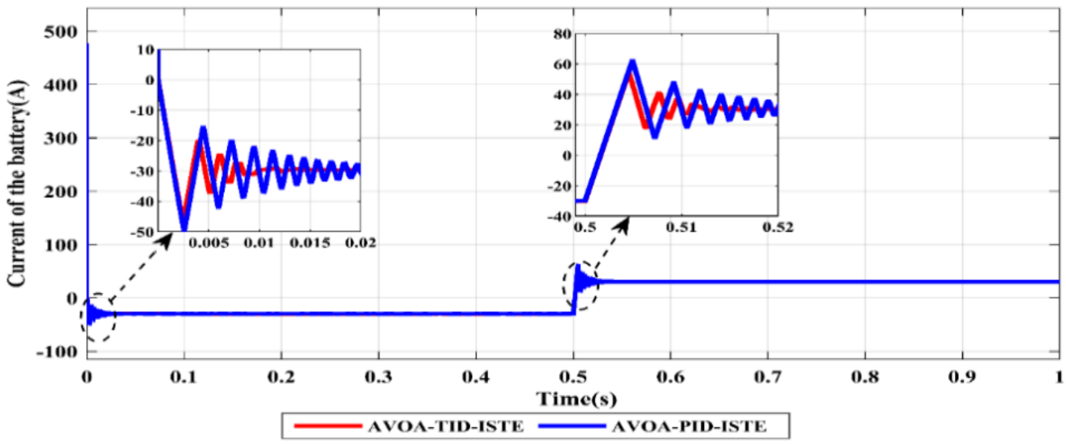
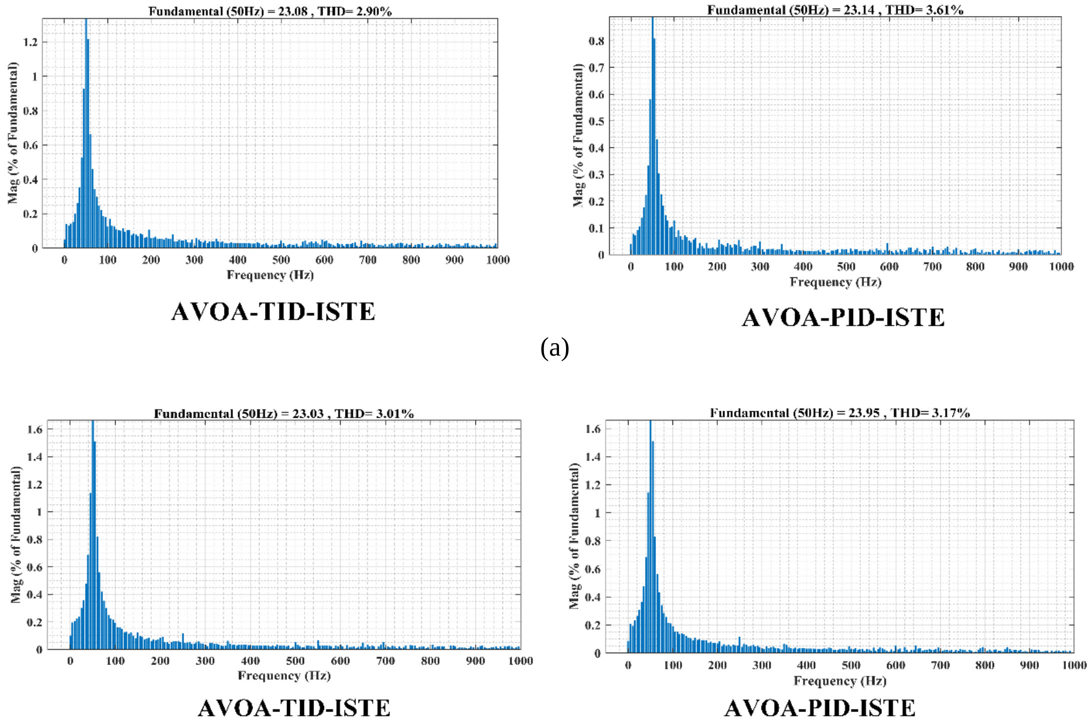


Figure 4. Battery current comparison

Figure 5 represents the total harmonic distortion (THD) of AC side current. In Figure 5(a), during charging mode, AVOA-TID-ISTE method provided THD with 2.90%, but AVOA-PID-ISTE provide 3.61%. In addition, In Figure 5(b), during discharging mode, the THD in IVOA-TID-ISTE method provided THD with 3.01%, and AVOA-PID-ISTE provide 3.17%. According to the simulation results, it can be concluded that the proposed AVOA-TID-ISTE controllers gives better results compared to the existing AVOA-PID-ISTE in terms of reducing power losses, improving the signal quality of the ac output voltage waveform by reducing THD.

One of the key features of using AVOA method includes the smoother implementation of optimized parameters into the studied model as the optimized parameters selected by the intelligent algorithms hold good for all the system operating conditions. Moreover, its ability to adaptively update the position and velocity of vultures is based on the best position found by the current vulture and the overall best position found by the entire flock. This allows the algorithm to quickly converge on the global optimum. However, this method has some limitations such as: AVOA being sensitive to the choice of parameters and the presence of noise which may affect on incompatibility of charging equipment of the station.



(a) (b)

Figure 5. THD of AC side current in: (a) charging mode and (b) discharging mode

4. CONCLUSION

In this paper, a bidirectional charging station has been studied, designed, and tested. The proposed solution is aimed to promote the integration of the automotive world with V2G and G2V capability in a smart grid scenario. To confirm the effectiveness of the proposed controller's topologies for grid-enabled system, its dynamic response, stability, robustness analysis is calculated and compared with the GA under identical operating conditions. AVOA has been shown to have a higher convergence rate and provide better solutions than GA when used to minimize the same fitness function. As a result, controllers developed using AVOA have been observed to have a better transient response, with lower overshoot and shorter rise and settling times, compared to those developed using GA. Therefore, it can be argued that the selection of PI parameters using AVOA is a more appropriate method than using GA. The results of the study demonstrate that the proposed AVOA-tuned TID with ISTE delivers the best dynamic response compared to other controllers. This proves the significance of the existing research article. Future work of this study can be promoted in the power grid with high-penetrated renewable energy to enhance the system power quality and reliability. Moreover, Improve the network by utilizing another recent algoithm.

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BIOGRAPHIES OF AUTHORS

Saleh Masoud Abdallah Altbawi he received the B.E. degree in Electronics in 2008 and the M.E degree from Sam Higginbottom University of Agriculture, Technology and Sciences in 2018. He is currently pursuing Ph.D. in electrical engineering at Universiti Teknologi Malaysia (UTM). His research interest includes artificial intelligence, power quality, algorithms, and power system. He has many publications in different publishers. He can be contacted at email: masoud@graduate.utm.my.

Prof. Madya Ir. Dr. Saifulnizam Bin Abdul Khalid he is an associate professor, Academic Coordinator/Laboratory Academic Coordinator, at the Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM). He received his B.Eng., M.E.E., and Ph.D. degrees from Universiti Teknologi Malaysia, Johor Bahru, Malaysia, in 1998, 2000, and 2009, respectively. application of artificial neural networks in power systems, power tracing, and smart metering applications. He can be contacted at email: saifulnizam@utm.my.

Dr. Ahmad Safawi Bin Mokhtar he is a senior lecturer, Academic Coordinator/Laboratory Academic Coordinator, at the Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM). He received his B.Eng. degree from Universiti Teknologi Malaysia, the M.Eng. degree in the University of Strathclyde University of Strathclyde, and Doctor of Philosophy (Ph.D.) in Electrical Power Engineering (2001–2005). His research interests include power systems analysis, electrical power engineering, and power quality. He can be contacted at email: safawi@utm.my.

Rayan Hamza Alsisi he received his Ph.D. degree in electrical and computer engineering from the University of Western Ontario, London, ON, Canada, in 2018. He is currently the Vice Dean for Development and Quality, at the Faculty of Engineering, Islamic University of Madinah, Saudi Arabia, where he is also an Assistance Professor. He is also a Consultant with Saudi Council of Engineers. He has authored many technical articles in journals and international conferences. His current research interests include wireless communications, digital communications, communication and information systems, information theory, signal processing, optical communications, the internet of things, communication networks, and electrical vehicles. He can be contacted at email: ralsisi@iu.edu.sa.

Zeeshan Ahmad Arfeen he is an Assistant Professor at "The Islamia University of Bahawalpur", Pakistan in the Department Electrical Engineering. He is a doctorate scholar from University Technology Malaysia (UTM) Skudai Johor Bahru, Johor, Malaysia. He is a senior member of the IEEE organization NJ. USA, member of IEEE Power and Energy Society (PES), life member IEEE Pakistan, and member of "The Institution of Engineers Pakistan" (IEP). Further, he is also a life member of Pakistan Engineering Council. He is an author of many high indexed Journals and a potential reviewer of more than 160+ papers ranked in ISI, Scopus, and Conference proceeding Journals. He can be contacted at email: zeeshan.arfeen@iub.edu.pk.

Hussain Shareef He received the Ph.D. degree in electrical engineering from Universiti Teknologi Malaysia (UTM), Malaysia, in 2007. He is currently a Professor with the Department of Electrical Engineering, United Arab Emirates University. He is also the Head of the Green Mobility Research Team, Emirates Center for Mobility Research. He has published more than 400 peer-reviewed journal articles in various fields related to power and energy systems and has more than 5674 citations with an H-index of 37. His research interests include power system planning, integration of renewable power sources, application of AI techniques in power systems, energy management, power quality, and electric vehicle grid integration. He can be contacted at email: shareef@uaeu.ac.ae.

Mehreen Kausar Azam she is a Ph.D. scholar of NED University. She has completed her Master's degree in Industrial Management and Bachelor's degree in Industrial and Manufacturing Engineering from NED University. She joined the Institute of Business Management (IoBM) in 2015. Previously Kausar was serving in a renowned MNC company where her key areas were quality control, inventory control, project management, and supply chain dynamics. Her research interest includes industry 4.0, risk management, electric vehicles, and sustainability. She has published various research papers in international journals and has authored many research papers, conference papers, and book chapters with renowned publishers. She can be contacted at email: mehreen.kausar@gmail.com.