Harmonic Distortion Prediction Model of a Grid - Connected Photovoltaic Using Grey Wolf Optimizer - Least Square Support Vector Machine

Zuhaila Mat Yasin
Faculty of Electrical Engineering
Universiti Teknologi MARA
Shah Alam, Malaysia.
zuhailamy74@gmail.com

Nur Ashida Salim
Faculty of Electrical Engineering
Universiti Teknologi MARA
Shah Alam, Malaysia.
nurashida606@uitm.edu.my

Nur Fadilah Ab Aziz
College of Engineering
Universiti Tenaga Nasional
Bangi, Malaysia.
NFadilah@uniten.edu.my

***Abstract*—This paper depicts a new technique for prediction of the total harmonic distortion (THD) in Grid-Connected Photovoltaic System. Global environmental awareness, increasing demand for energy and down price tendency has led to new opportunities for utilization of renewable energy resources such as photovoltaic (PV) system. The integration of PV system to the grid must comply with the relevant standards given by the utility company. However, the output of PV somehow causes a harmonic distortion as the installation of inverter. The output of PV mainly depends on solar irradiation. Therefore, solar irradiation is selected as one of the input to the prediction model. The hybridize method of heuristic-algorithm namely Grey Wolf Optimizer-Least Square Support Vector (GWO-LSSVM) is introduced in order to improve the prediction accuracy. GWO is inspired by the leadership hierarchy and hunting mechanism of grey wolf in nature. The top hierarchy of grey wolf that considered as the fittest solution is alpha, followed by beta, delta and omega. The optimization process implementing three main steps such as hunting, searching for prey, encircling prey and attacking prey. GWO is utilized to optimize the parameters in LS-SVM model. The results showed that GWO-LSSVM predict more accurate than PSO-LSSVM and LSVM.**

Keywords— Total Harmonic Distortion (THD), Grid-Connected Photovoltaic (CGPV), Grey-Wolf Optimizer, Least-Square Support Vector Machine

I. INTRODUCTION

With the development of social economy, a large number of Power Quality (PQ) problems have drawn the attention of power sectors and the users such as harmonic, voltage sag and voltage deviation [1]. The occurrence of harmonic will affect the safe operation such as insulation ageing, loss of power supply equipment, and the interference to electrical equipment. The continuous growth of renewable energy recently creates new requirements for electricity utilities to analyse the impact of renewable energy resources to PQ [2].

Photovoltaic (PV) power generation is increasing rapidly as it utilize energy from solar. Solar energy is absorbed by solar panel and DC power is generated. The DC power is then converted to the synchronous AC power and integrated to the AC grid through the grid-connected inverter [3]. Fig. 1 presents the global capacity of PV during 2008– 2018 [4] .

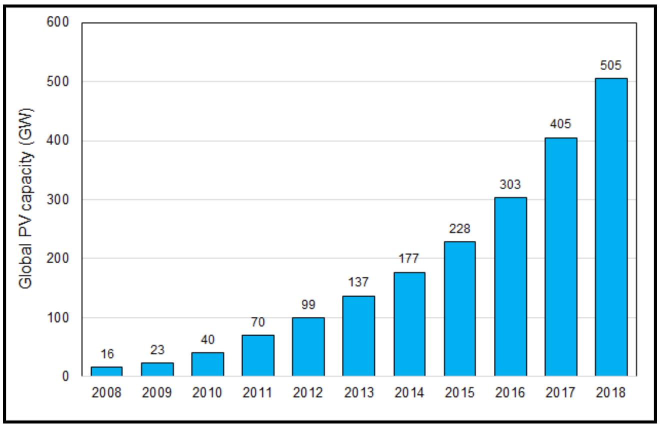

Fig. 1. Global PV capacity (year 2008-2018)

Nowadays, PV technologies took places in replacing non-renewable sources such as fossil fuel. Although PV technology have many advantages such as the ability of PV to produce electricity without any pollution to the environment, PV technology also has adverse effect such as power quality issues, harmonic, power loss increase and reverse power flow [5], [6]. The cause of power quality in the grid-connected photovoltaic can be straight links with the presence of inverter devices. As the non-linear system is used, the harmonic distortion will occur and cause power quality disturbance in the output. Power quality issue such as Total Harmonic Distortion (THD) has become an increasingly significant concern due to the increment of PV integrated to the grid system [7].

Reference [7] has showed the impact of solar irradiance to current and voltage THD in simulation model developed in Simulink. Solar irradiance is recorded as 1.43% maximum and 1.32% minimum. Hence, the result denotes that solar irradiance does not have direct effect on the voltage generated of the PV system. The major relation of solar irradiance level was observed on the level of THDi%. During early at 9.15AM, at 238 W/m2 of Solar Irradiance the THDi% value is 15.16% and decreases to 4.48% in the afternoon at 1.08PM during maximum solar irradiance of 1113 W/m2. Reference [8] has presented two techniques to predict PV power quality focusing on THD current namely extreme learning method (ELM) and random forest (RF) method. However, the prediction values of irradiance-dependent THDi max above 12% is neither methods are able to successfully predict likely due to a poor data quality, and with short term weather forecasts.

978-1-7281-2658-6/19/$31.00 ©2019 IEEE

Predicting the levels of harmonics caused by renewable energy resources such as PV is complex due to the availability of various inverter topologies, which employ different control method [9], [10], [11]. However, in order to ensure the safety and economic operation of power grid, an accurate prediction of THD level need to be developed [12], [13]. A new technique namely Grey-Wolf Optimizer Least-Square Support Vector Machine (GWO-LSSVM) is proposed to predict the THD level in grid connected PV System.

II. Total Harmonic Distortion (THD)

The data studied in this paper are taken from Green Energy Research Centre (GERC), Malaysia. The data are taken from both Monocrystalline and Polycrystalline PV modules. Overall, there are four array configuration at which for Poly-Crystalline, there are two strings for array configuration which string one have 12 units' module and string two have 11 units' module. The nominal power of Polycrystalline PV module is 5405 kWp. While the nominal power for Monocrystalline is 9 kWp. These PV modules are placed on a roof top and some are put at the field near the office. In this study, three sets of data were obtained namely time, solar irradiance and THD values. The data were recorded at every 5 minutes in a day. The number of data used is 1196 inclusive of input and output. Table I indicates which data sets are input and output.

TABLE I. Type of Data

Data	Type of Data
Time	Input
Solar Irradiance	Input
THD A L1	Output
THD A L2	Output
THD A L3	Output

THD A L1, THD A L2, and THD A L3 are the three phase system of the current which stand for red, yellow, and blue line respectfully. The characteristic of the inputs of time and solar irradiance is shows in Fig. 2.

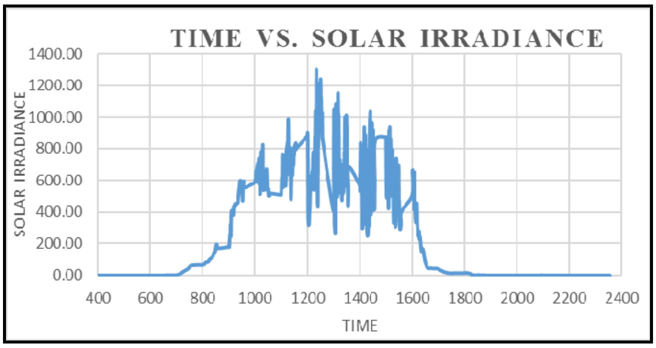

Fig. 2. Solar Irradiance vs time characteristic

As presented in Fig.2, the solar irradiance is at maximum during 12.00 p.m at which sun is in solar noon. The integration of PV system to the grid must comply with the relevant standards given by the utility company. In this study, the standards for current distortion limits is referring to the IEEE standards 519-1992 as shown in Table I [14]. The IEEE Standard 1547 endorse the AI criteria in Table II such Isc/IL < 20*, ITHD = 5%. For the standard of PV system connected to the grid, the IEEE 1547 & IEC 61727 standards is shown in Table II. The data of the PV system taken form GERC is comply with these two regulation. Table III shows the regulation in IEEE in order to connect the PV system to the grid connected. The harmonic distortion produced by the PV generator must be lower than the percentage of THD given for every odd component. Noted that only odd component is concern for current harmonic distortion.

TABLE II. Harmonic Current Distortion Limit (Adapted from IEEE 519-1992)

Maximum Harmonic Current Distortion in % of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	**<11**	**11≤h<17**	**17≤h<23**	**23≤h<35**	**35≤h**	**TDD**
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonics are limited to 25% of the odd harmonic limit. TDD refer to Total Demand Distortion and is based on the average maximum demand current at the fundamental frequency, taken at the PCC.						
*All power generation equipment is limited to these values of current distortion regardless of $I_{SC}I_L$						
I_{SC} = Maximum short circuit current at PCC IL = Maximum demand load current (fundamental at PCC) h = Harmonic number						

TABLE III. Standards of Interconnection of PV System to the Grid

Issue	IEC 61727		IEEE 1547	
Nominal Power	10kW		30kW	
Harmonic Currents Limits	Harmonics (nth)	THD (%)	Harmonics (nth)	THD (%)
	3-9	4	3-9	4
	11-15	2	11-15	2
	17-21	1.5	17-21	1.5
	23-33	0.6	23-33	0.6
			>35	0.3
Maximum Current THD	5%		5%	

III. Development of LSSVM for Prediction of THD Level

Least Square Support Vector Machines (LSSVM) is a modification based on Statistical Learning Theory (SLT). LSSVM aiming to narrow the prediction error through iterative trials and errors. Instead of non-negative errors in the cost function, LSSVM applies square errors. In the function formulation, LSSVM use equality constraint. Therefore, LSSVM lead to easier and faster training task thus simpler optimization can be obtained [15]. Model of LSSVM for regression is shown in (1):

$$y(x) = \sum_{l=1}^{N} \alpha_l K(x, x_l) + b \quad (1)$$

Several kernel function $K(x,x_l)$ is available such as Radial Basis Function (RBF) kernel, Polynomial kernel or Linear

Kernel Function. By applying a different kernel function, the different result in performance of LSSVM are obtained. There are two parameter used in this study that are tuning parameter that associated with RBF kernel, σ^2 and regularization parameter, γ. Fig. 2 illustrates the flowchart of LSSVM to predict the THD level in GCPV system. Firstly, the data is divided into two categories which are training and testing. Then, the hyper parameters were initialized. The training process are repeated until it converged. In this paper, Mean Square Error (MAE) and coefficient of determination (R^2) are used to measure the accuracy of the proposed prediction model. MAE and R^2 were calculated based on (2) and (3).

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |THD_{actual} - THD_{predicted}| \tag{2}$$

$$R^2 = \frac{\sum(THD_{actual} - THD_{predicted})^2}{\sum(THD_{actual} - THD_{average})^2} \tag{3}$$

Where THD_{actual} is the measured THD

$THD_{predicted}$ is the THD obtained using LSSVM

$THD_{average}$ is the average THD obtained

IV. Development of GWO-LSSVM

The prediction performance of LSSVM depends on the preference of RBF parameters. Therefore, to ensure the accurate prediction, GWO is proposed to optimize the value of RBF parameter in hybrid model namely GWO-LSSVM. GWO is inspired by the leadership hierarchy and hunting mechanism of grey wolf in nature. The top pack of the Grey Wolf is the ruling Alpha (α)wolves, followed by Beta (β) wolves, the third layer is Delta (∂) wolves, and the last layer is Omega (Ω) wolves. The hunting mechanism implemented are tracking, encircling and attacking prey [16].

In social hierarchy, the fittest solution is the Alpha, subsequently Beta and the third best solution is Delta. The rest candidates belong to Omega. These social hierarchy will be hunting (optimize) and it guides by Apha, Beta, Delta and Omega wolves will follow them. These pack of wolves are known as the search agents. In GWO codes, the Alpha, Beta and Delta are based on the number of dimension in the function details. Dimension is the number of variables used as the problem proposed. Hence in this study, the dimension is referring to the values of gamma and sigma. After the initialization of Alpha, Beta and Delta, the position of the search agent is determined to start the hunting step. Grey wolves encircling the prey during hunting. Therefore, the position of the search agent is depending to the size of search agent, dimension, upper and lower bound. The current iteration is defined as t. $\vec{A}$ and $\hat{C}$ are the coefficient vectors. These both vectors are calculated referring to (3) and (4) respectively [16].

$$\vec{A} = 2\vec{a}\cdot\vec{r_1} - \vec{a}(t) \tag{3}$$

$$\vec{C} = 2\cdot\vec{r_2} \tag{4}$$

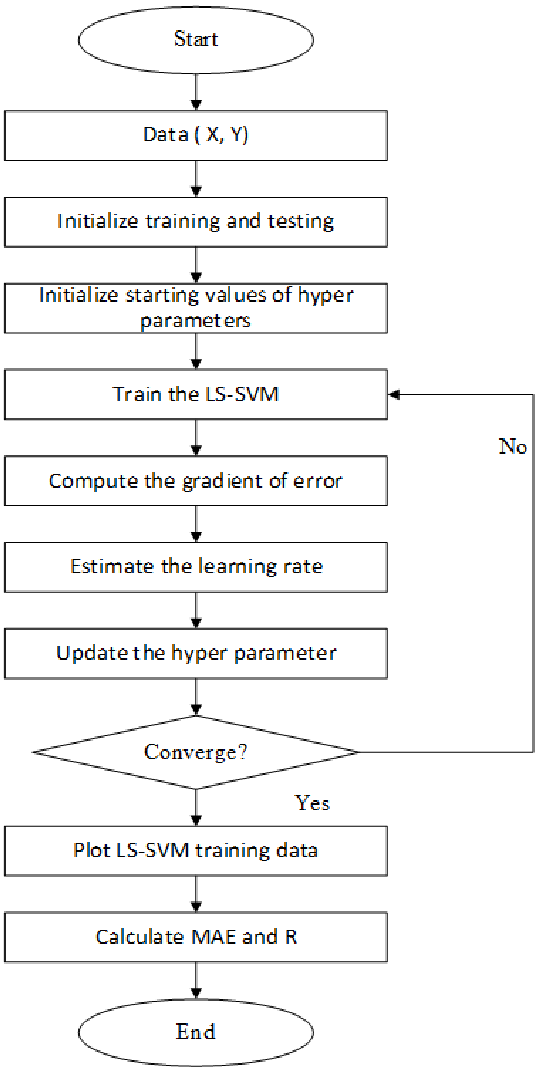

Fig. 3. Flowchart of LSSVM

For encircling step, position of grey wolf and prey were defined as *(X,Y)* and *(X*,Y*)*. The position of grey wolf that involve in hunting activities need to be updated according to prey positions. The mathematical model's behavior for encircling prey are represented as shown in (5) and (6):

$$\vec{D} = |\vec{C}\cdot\vec{x_p}(t) - \vec{x}(t)| \tag{5}$$

$$\vec{x}_{(t+1)} = \vec{x_p}(t) - \vec{A}\cdot\vec{D} \tag{6}$$

Where t - the current iteration

$\vec{x_p}$ - The prey position

$\vec{x}$ - The grey wolf position

For the hunting part, grey wolves must be able to recognize the place of the prey and surrounded it. This activity was conducted through Alpha. For the simulation of the hunting behavior of grey wolves, the potential location of the prey should be known by the Alpha (best candidate solution), Beta and Delta. The grey wolves end the hunt with the prey when it stops moving. For attacking step, movement of grey wolf approaching the prey has define in terms of α. The decrease values of α means that the grey wolf starts to approach the prey. If value of A is decrease low than 1 *(|A|<1)*, it will influence grey wolf to attack the prey. If A value is increase more than 1 (*A|>1*), grey wolf is forced to move away from the prey. Lastly, search process starts with the production of the grey wolf's random population. The position of the prey is estimated over the course of iterations. To point out the exploration and exploitation, the parameter of α is reduced from 2 to 0. After the candidate solution diverged *(|A|>1)*, from the prey and converged *(|A|<1),* GWO algorithm will terminate. It means that the satisfaction of criterion was end. The overall flowchart for the proposed technique is illustrated in Fig. 4. The objective of the optimization is to minimize the MAE.

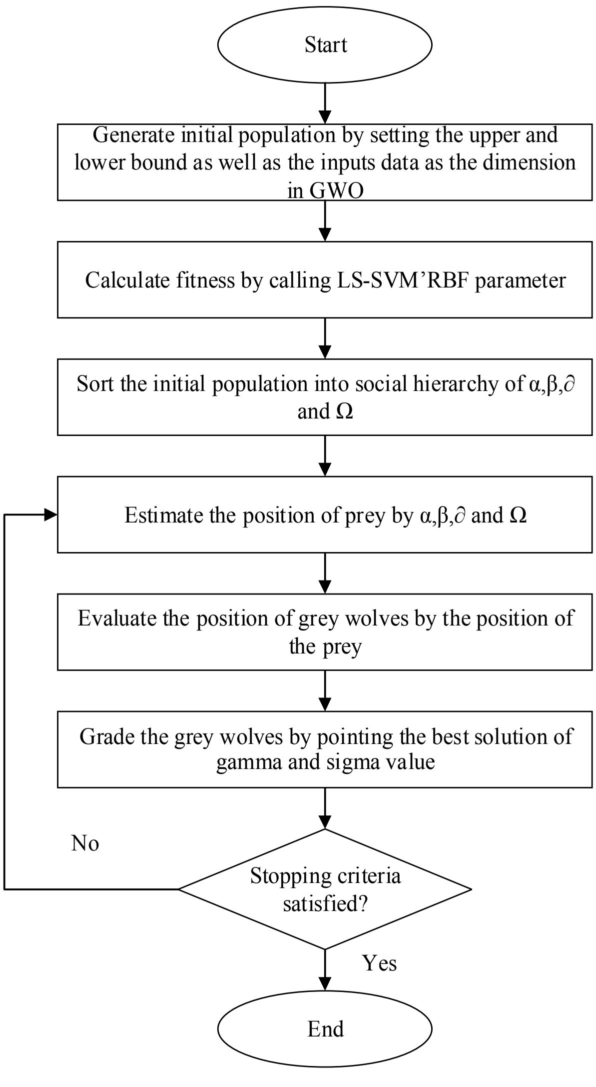

Fig. 4. Flowchart of GWO-LSSVM

V. RESULT AND DISCUSSION

By using cross-validation techniques, the LSSVM result is first obtained in this study. Table IV tabulates the results of LS-SVM obtained at the three levels of THD. THD AL3 obtained minimum MAE as compared to other levels. Fig. 5. Fig. 6 and Fig. 7 shows the results of LSSVM during training for different THD levels which are THD A L1, THD A L2 and THD A L3 respectively. X_1 and X_2 defined the inputs of the LSSVM which are time and solar irradiance. The different THD value for all three levels are depending to the different loads connected to each level.

TABLE IV. RESULTS OBTAINED USING LSSVM

Line	Gamma (ɤ)	Sigma (σ^2)	Mean Absolute Error (MAE)	Regression (R^2)
THD A L1	6.0027	0.0212	0.2682	0.8586
THD A L2	4.0750	0.0560	0.1967	0.8864
THD A L3	11.5977	0.0018	0.1965	0.9279

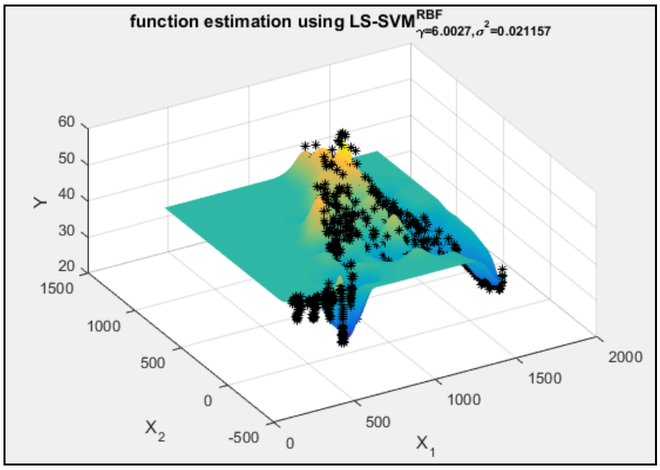

Fig. 5. THD A L1

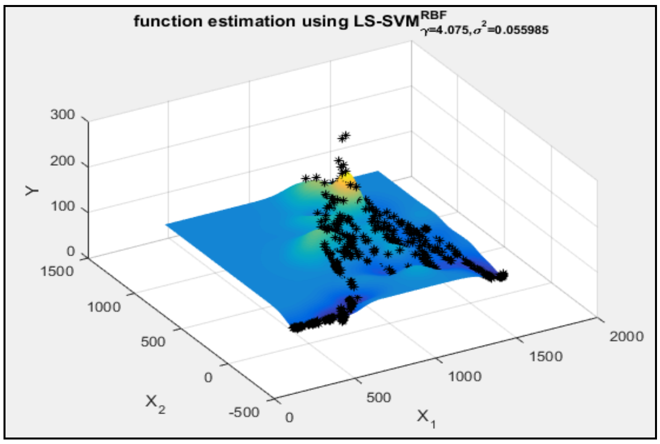

Fig. 6. THD A L2

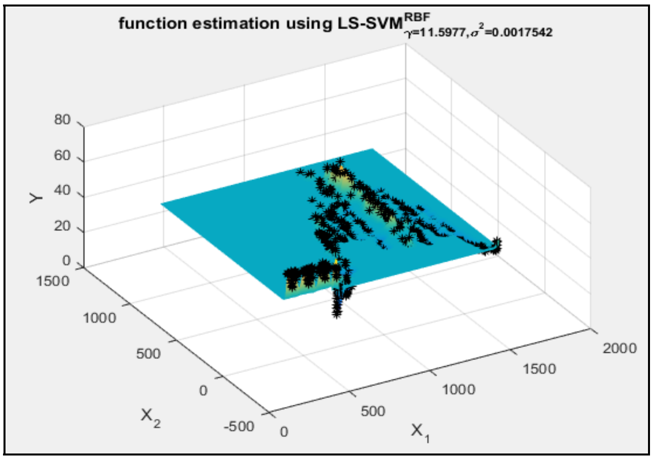

Fig. 7. THD A L3

In order to improve the performance of LSSVM, GWO is hybridized to determine the optimal RBF parameters. Then, the performance of GWO-LSSVM is compared with PSO-LSSVM. The parameters of both algorithm such as number of search agent and maximum iteration are presented in Table V. The results obtained from both techniques are tabulated in Table VI.

TABLE V. PROPERTIES SETTING

	GWO -LSSVM	PSO-LSSVM
Search Agent	20	20
Max Iteration	50	50

TABLE VI. COMPARISON OF MAE

Line	Gamma (γ)	Sigma (σ^2)	Mean Absolute Error *(MAE)*	
			GWO - LSSVM	PSO-LSSVM
THD A L1	1000	113.2859	0.2607	0.2625
THD A L2	1000	103.116	0.1664	0.1723
THD A L3	1000	107.787	0.0257	0.0270

From Table VI, it can be observed that the MAE produced by GWO-LSSVM are lower than the MAE produced by PSO-LSSVM for all THD level. This results indicated that GWO-LSSVM has higher accuracy as compared to PSO-LSSVM. Nevertheless, the performance of PSO-LSSVM is better than the performance of LSSVM. It can be concluded that the performance of LSSVM can be improved by choosing the optimal RBF parameters. The convergence graph for all cases are illustrated in Fig. 8, Fig. 9 and Fig. 10.

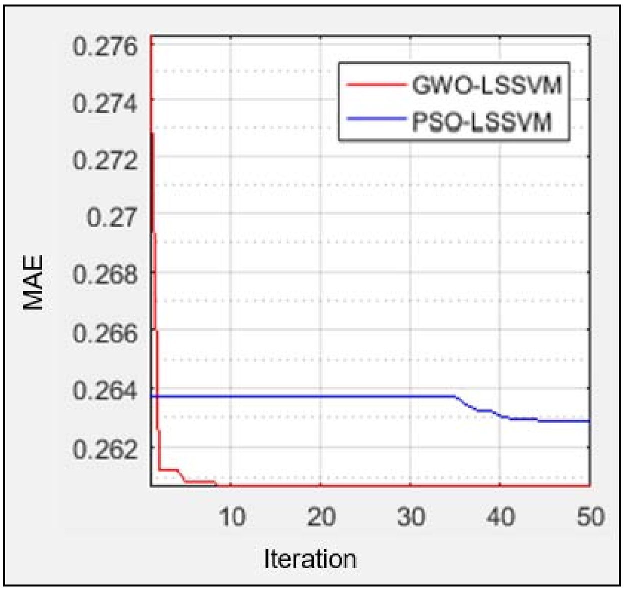

Fig. 8. Convergence curve for THD A L1

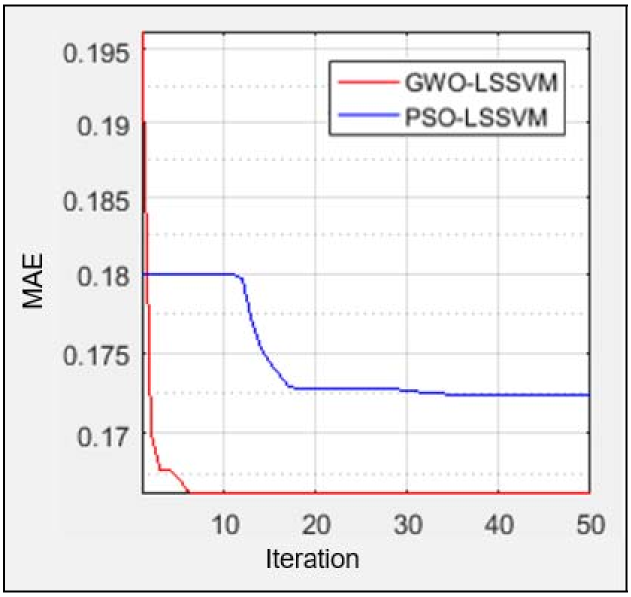

Fig. 9. Convergence curve for THD A L2

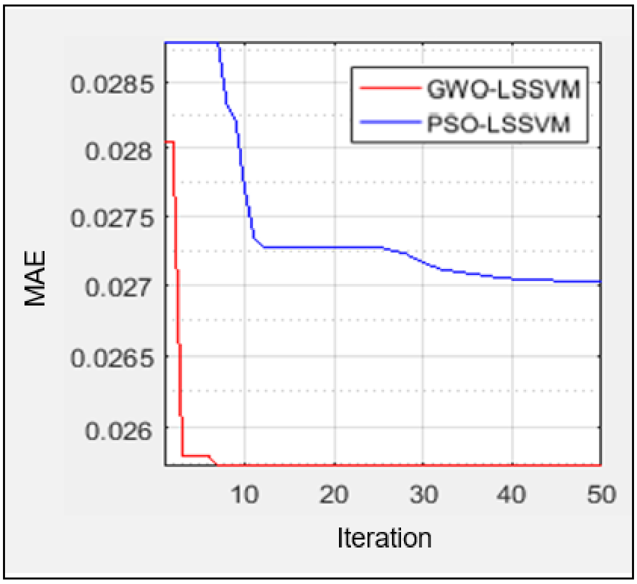

Fig. 10. Convergence curve for THD A L3

From Fig. 8, it can be seen that GWO-LSSVM converge at minimum MAE compared to PSO-LSSVM. GWO-LSSVM converge at 4^{th} iteration meanwhile PSO-LSSVM converge at 6^{th}. Similar observation could be seen in Fig. 9 where GWO-LSSVM converged faster and at minimum MAE. From these three figures, it can be observed that GWO-LSSVM converged faster than PSO-LSSVM. Furthermore, GWO-LSSVM provide more accurate results as compared to other technique.

VI. Conclusion

PV system is now a popular solution of the future problem regarding to non-fossil fuel depletion and demanding renewable energy in Malaysia. As the Grid-Connected PV system is widely used in urban areas, the inverter is required to modify the DC output of PV module to AC output demanded by customers. As known inverter can cause so much electrical disturbance especially harmonic distortion. Hence, the hybrid technique namely Grey-Wolf Optimizer – Least- Square Support Vector Machine (GWO-LSSVM) is proposed for the prediction of Total Harmonic Distortion (THD) in the Grid-Connected System. The proposed technique had shown a better prediction accuracy as compared to other techniques such as LSSVM and Particle Swarm Optimization Least- Square Support Vector Machine (PSO-LSSVM).

Acknowledgment

The authors would like to thank the Research Management Institute (RMI), Universiti Teknologi MARA, Malaysia and the Ministry of Higher Education (MOHE), Malaysia through research grant 600-IRMI/DANA 5/3/BESTARI (121/2018) for the financial support of this research.

References

[1] J. Song, Z. Xie, J. Zhou, X. Yang, and A. Pan, "Power quality indexes prediction based on cluster analysis and support vector machine," *CIRED - Open Access Proceedings Journal*, 2017.

[2] P. S. De Oliveira, M. A. A. Lima, A. S. Cerqueira, C. A. Duque, and D. D. Ferreira, "Harmonic analysis based on scica at PCC of a grid-connected micro solar PV power plant," in *Proceedings of International Conference on Harmonics and Quality of Power, ICHQP*, 2018.

[3] X. Tong, M. Zhong, X. Zhang, J. Deng, and Z. Zhang, "Voltage regulation strategy of AC distribution network based on distributed PV grid-connected inverter," *The Journal of Engineering*, 2019.

[4] REN21, "Advancing the global renewable energy transition," 2018.

[5] T. R. Ricciardi, W. Freitas, F. K. Taniguchi, G. R. T. Hax, R. Moya, and G. B. Archilli, "Measurement based power quality analysis of real distribution networks with high PV penetration," in *Proceedings of International Conference on Harmonics and Quality of Power, ICHQP*, 2018.

[6] O. S. Nduka and B. C. Pal, "Harmonic Domain Modeling of PV System for the Assessment of Grid Integration Impact," *IEEE Transactions on Sustainable Energy*, 2017.

[7] M. Ayub, C. K. Gan, and A. F. A. Kadir, "The impact of grid-connected PV systems on Harmonic Distortion," in *2014 IEEE Innovative Smart Grid Technologies - Asia, ISGT ASIA 2014*, 2014.

[8] J. Rodway, P. Musilek, S. Misak, and L. Prokop, "Prediction of PV power quality: Total harmonic distortion of current," in *2013 IEEE Electrical Power and Energy Conference, EPEC 2013*, 2013.

[9] G. Todeschini, S. Balasubramaniam, and P. Igic, "Time-domain Modeling of a Distribution System to Predict Harmonic Interaction Between PV Converters," *IEEE Transactions on Sustainable Energy*, 2019.

[10] B. Cao, L. Chang, and R. Shao, "A simple approach to current THD prediction for small-scale grid-connected inverters," in *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, 2015.

[11] M. Panoiu, C. Panoiu, and L. Ghiormez, "Neuro-fuzzy modeling and prediction of current total harmonic distortion for high power nonlinear loads," in *2018 IEEE (SMC) International Conference on Innovations in Intelligent Systems and Applications, INISTA 2018*, 2018.

[12] H. Hu, Q. Shi, Z. He, J. He, and S. Gao, "Potential harmonic resonance impacts of PV inverter filters on distribution systems," *IEEE Transactions on Sustainable Energy*, 2015.

[13] P. J. Bhaskara Rao and B. Srikanth, "Harmonic reduction in grid connected solar PV system by using SVPWM technique," *International Journal of Applied Engineering Research*, 2016.

[14] IEEE Standard, *IEEE Application Guide for IEEE Std 1547(TM), IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems*. 2009.

[15] M. A. A. Aziz, Z. M. Yasin, and Z. Zakaria, "Prediction of photovoltaic system output using hybrid least square support vector machine," in *2017 7th IEEE International Conference on System Engineering and Technology, ICSET 2017 - Proceedings*, 2017.

[16] S. Mirjalili, S. M. Mirjalili, and A. Lewis, "Grey Wolf Optimizer," *Advances in Engineering Software*, vol. 69, pp. 46–61, 2014.