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Optimal control strategy of photovoltaic system based autonomous micro grid for power quality improvement

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ABSTRACT

Due to the increasing number of distributed generation units being used in remote regions, the need for reliable and flexible operation of these systems has led to the development of microgrid technology. When a microgrid operates in an autonomous mode, it can experience unpredictable loads and other factors that can affect its operation. An optimal control mechanism is required to maintain the system's stability. Hence, in this paper optimal control strategy of autonomous microgrid for power quality improvement is presented. A test case of single phase 3.5 kW photovoltaic (PV) system based autonomous micro grid is considered. Particle swarm optimization (PSO) and Harris hawks optimization (HHO) optimal control strategies are implemented under standard test case and variable test cases. In all the cases PV mean voltage-Vmpv (V), PV mean current-Impv (A), rms voltage-Vrms (V), rms current-Irms (A), mean PV power-Ppv (W), autonomous grid power-Pg (W), efficiency (%), total harmonic distortion (THD) (%), inverter losses (%) are evaluated. In all the cases HHO optimal control strategy for autonomous microgrid exhibits the best performance in comparison with PSO optimal control strategy. The inverter efficiency is improved, inverter losses are reduced and the THD is improved.

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1. INTRODUCTION

Despite the COVID-19 pandemic, the global photovoltaic (PV) market grew significantly in 2020. At least 139.4 gigawatts of PV systems were installed globally in 2020. Data collected by Bloomberg New Energy Finance shows that the Chinese PV market reached a level that it experienced in 2017. This marked a return to a market that was at its peak in 2017. China remained the world's leader in terms of total installed capacity with a total of 253,4 gigawatts in 2020. Outside of China, the global market grew at a robust rate of 14% in 2020 to reach 90 GW. Germany led the European market in 2020, followed by the Netherlands, Spain, Poland, and France. The US saw its market increase to a new record of 19.2 gigawatts. Other key markets that saw significant new additions in 2020 were India, Australia, South-Africa, and Taiwan [1].

Preliminary data shows that South Africa and Mexico could have added over a gigawatt of capacity. The top 10 countries in 2020 represented almost 78% of the global annual PV market. In terms of total installed capacity, the top 10 countries account for over 3.0 GW of the total. Despite the robust growth, the global market concentration remained relatively low. Countries such as Spain, Italy, and Turkey now have enough capacity to meet their annual electricity demand. PV is currently contributing to the decarbonizing of the electricity mix by saving about 875 million tons of CO2eq. Despite the progress, more is needed to be done to fully implement the targets set by the COP21. Global PV installed capacity is shown in Figure 1.

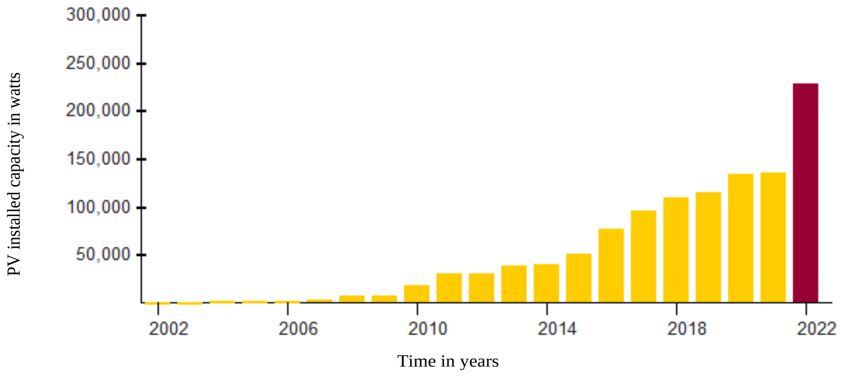

Figure 1. Global PV installed capacity

Since ancient times, the sun has been regarded as a vital energy source. India has the potential to generate thousands of trillions of kilowatt hours of solar energy annually. With the increasing penetration of solar power in India, the country is expected to gain immense potential. Its ability to provide stable and cost-effective power is expected to make it a preferred choice for various urban and rural electrification projects. Since solar is the most secure and abundant source of energy, it is considered as the most practical option for addressing the country's energy security concerns. Through the use of solar energy, millions of villagers in India have been able to meet their lighting and cooking needs in an environment-friendly manner. The social and economic benefits of solar energy include reduction in drudgery and pollution, as well as the creation of opportunity for villagers. India's solar energy sector has also emerged as a major player in the grid-connected power generation industry. It supports the government's goals of sustainable growth and energy security [2].

A study conducted by the National Institute of Solar Energy estimated that India has the potential to generate 748 gigawatts of solar energy. This figure includes the area that would be covered by solar PV modules. On January 11, 2010, India's Ministry of Environment and Climate Change launched the National Solar Mission (NSM). This initiative aims to promote solar energy as a solution to the country's energy security challenges. The objective of the mission is to make India a global leader in solar energy by accelerating the deployment of solar technology across the country. To achieve this, the government has launched various initiatives such as the solar park scheme, the viability gap funding (VGF) scheme, the defense scheme, and the bundling scheme [3].

Various policies were also taken by the government to promote solar energy. These include the declaration of a trajectory for the implementation of the renewable purchase obligation. Other measures included the establishment of a framework for the competitive bidding process for solar power projects [4]. In 2019, India became the fifth global leader in solar power deployment. This achievement was made possible through the significant increase in solar power capacity over the last five years. Global PV installed capacity in India is show in Figure 2 [5].

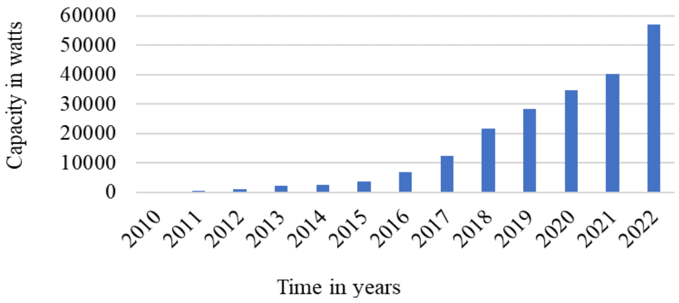

Figure 2. PV installed capacity in India

2. AUTONOMOUS MICRO GRID

Autonomous microgrid is a type of energy generation system that can provide continuous power to small communities. It typically uses a combination of different energy sources such as wind, solar, and battery storage to meet its needs. These resources are independent of the central utility grid and can be used to recharge electric cars or other distributed energy systems. The concept of autonomous microgrids and traditional grids is quite different since they both function similarly. Although a microgrid can provide power to a small community, it is also part of the larger network. This is because they often take electricity from the grid and feed it into it. The ability to balance the demand and supply of energy across the network is very important for smart grid design. This is because society's growing reliance on renewable energy sources such as wind and solar power is forcing the need for more efficient and resilient energy systems.

Unlike traditional grids, which rely on the central utility to provide power, microgrids can also operate independently. They can decouple from the grid and provide reliable power to their communities during times of grid malfunction. In addition, they can help manage their energy costs by using their autonomy to reduce the demand for electricity. For instance, if the local community experiences high utility rates during a spike in demand, it can use the electricity generated by the microgrid to meet its needs. Some control tools for microgrids require that a person manually disconnect from the grid. Others allow them to automatically disconnect from the system. Since a microgrid is a self-contained device, it's important to think of it as a gateway that connects all of its electricity flows through. Regardless of the amount of energy resources that are stored within a microgrid, it's still considered a standalone power station.

3. LITERATURE REVIEW

A microgrid is a type of distributed generation system that uses a combination of electrical and non-conventional energy sources to generate electricity. These types of systems can be built using various types of energy such as wind turbines, fuel cells, and solar energy. Proportionate sharing of load in hybrid autonomous micro grid performance is presented in Aggarwal *et al.* [6]. Optimal control strategies for autonomous microgrid are presented in Zhang and Fletcher [7] and distributed control is presented in Toyoshima *et al.* [8].

A microgrid can function as either a connected system or isolated from the grid. The quality of its power supply can be a concern when it's connected to the main grid. Unbalanced voltage can also affect the system's operation. A solid-state circuit breaker (CB) is then connected between the utility grid and the microgrid to isolate the system. When the voltage unbalanced is not as intense as it should be, the CB stops acting and causes the system to experience continuous unbalanced voltage. This issue is usually caused by the lack of power quality. In recent years, the field of power system rectification has undergone a significant increase in terms of its methodologies. Koyanagi *et al.* [9] explained electricity cluster-oriented network (ECCON) based control approach is implemented. Islanding detection is presented in Wang *et al.* [10].

The electric power quality of a system is affected by the frequency and magnitude of its power distribution bus voltage. This means that the energy that the customer uses must be interrupted from its reliability perception. Other factors such as harmonic content, voltage unbalance, and reactive power demand are also known to affect the quality of the electricity supply. In addition to these factors, other factors such as the frequency and magnitude of its voltage unbalance can also affect the quality of the electricity supply. One of the most common methods that can be used to address this issue is by implementing a current control loop [11] and the relevant studies are presented in [12]–[14].

A dynamic generator (DG) is a type of electrical system that can provide a flexible and robust solution to the issue of the electricity supply. It can also be used in both islanded and grid tied mode. In order to improve the performance of its controllers, various modification techniques have been carried out. One of the most common modification techniques that has been carried out is by implementing a current control loop. This method can be used to improve the power quality of a system by implementing a dynamic volt-ampere reactive (VAR) converter and a shunt active power filter. In order to regulate the frequency and voltage of the electricity supply, a microgrid can be operated in either islanded or grid tied mode. Droop control technique is another modification technique that can be used to improve the power quality of a system by implementing a reactive and active power control system. This method has been extensively used in the V and I phase of the project to provide PQ control in a microgrid [15] and the relevant studies are presented in [16]–[19].

In this paper a test case of single phase 3.5 kW PV system based autonomous micro grid is considered. Particle swarm optimization (PSO) [20] and Harris hawks optimization (HHO) [21] based optimal control strategy of autonomous microgrid for power quality improvement is presented. The optimal control strategies are implemented under standard test case and variable test cases. In all the cases Vmpv (V), Impv (A), Vrms (V), Irms (A), Ppv (W), Pg (W), efficiency (%), THD (%), inverter losses (%) are evaluated. In all the cases HHO optimal control strategy for autonomous microgrid exhibits the best performance in comparison with PSO optimal control strategy. The inverter efficiency is improved, inverter losses are reduced and the THD is improved.

4. PARTICLE SWARM OPTIMIZATION

In 1995, Eberhart and Kennedy developed the PSO algorithm, which simulates the social behavior of a swarm of birds, fish, or bees. The goal of this algorithm is to create a global functional pattern of interactions between different groups of organisms by analyzing their local environment. The concept of swam intelligence is a collective behavior of unsophisticated agents that can be defined by their interactions with their surroundings [22]. The journey of a swarm of bees is the most common example of how the PSO approach can be applied to the social behavior of organisms. In the field, imagine that a group of bees is looking for a higher concentration of flowers. However, instead of finding the flowers in a given location, the swarm starts looking for them randomly [23].

The first stage of the process is when the bees start remembering the locations of the flowers they found. They then start to identify the other locations of the flowers that their neighbors have found. In this case, the bees are more likely to react to the presence of the most flowers in the area. They then start to move in both directions to find the best position. The movement of the bees is influenced by the social influence that it has gained from its surroundings. The flowchart of PSO algorithms is shown in Figure 3. The velocity and position of the particles are updated by (1) and (2).

$$V_i^{k+1} = V_i^k + C_1 \times rand\,(v) \times \left(pbest_i - S_i^k\right) + C_2 \times rand\,(v) \times \left(gbest_i - S_i^k\right) \tag{1}$$

$$S_i^{k+1} = S_i^k + V_i^{k+1} \tag{2}$$

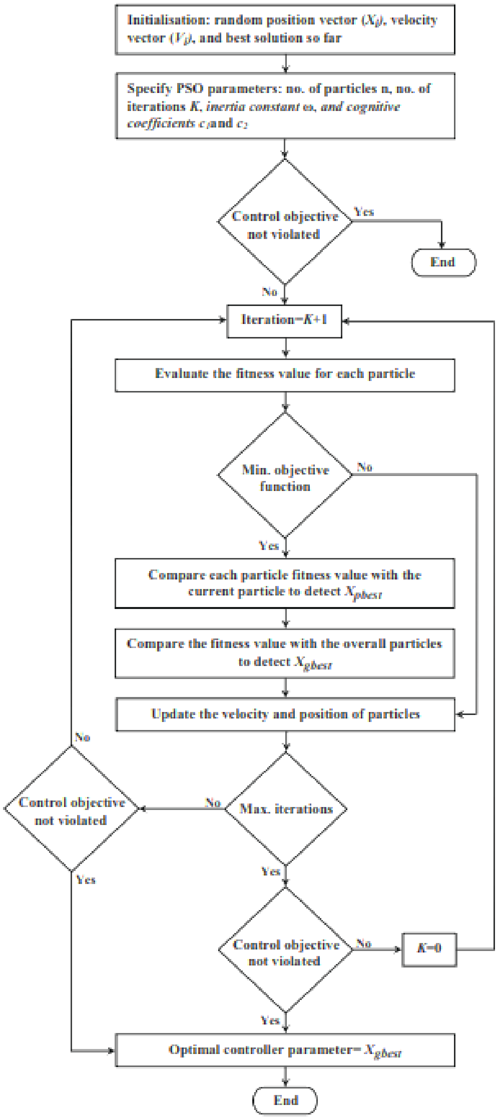

Figure 3. PSO flowchart

5. HARRIS HAWKS OPTIMIZATION

The HHO algorithm is a widely used gradient-free optimization method that can be used for various tasks, such as searching and exploitation. It was first published in 2019 by the functionally graded cellular structures (FGCS), and it has gained widespread attention due to its high performance and flexible structure [24]. The main idea of the HHO method is to create a cooperative environment where Harris' hawks can chase each other. This is done through the use of surprise pounce. There are many suggestions that can be used to enhance the functionality of this system [25]. The flowchart and exploration phases are presented in Figures 4 and 5 respectively.

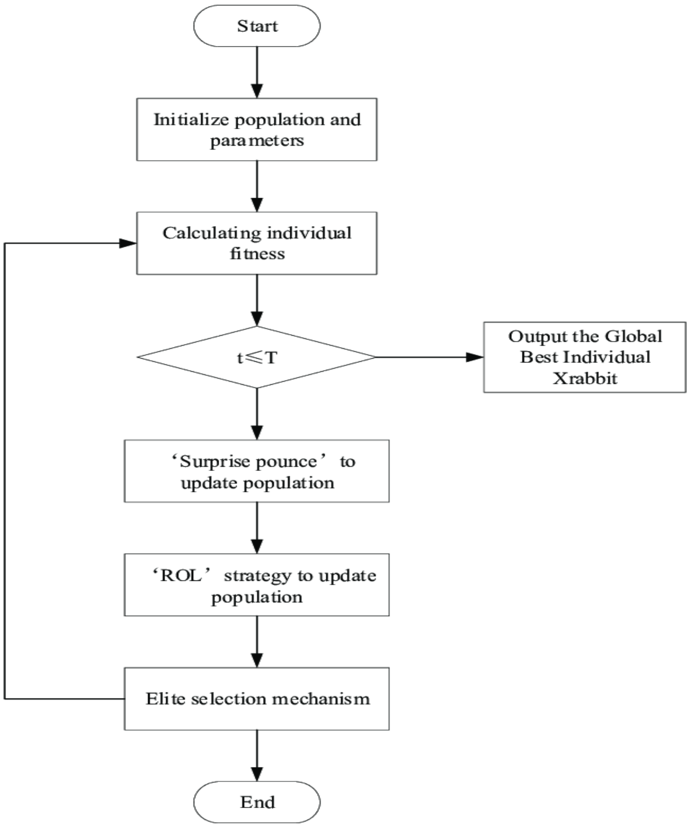

Figure 4. Flowchart of HHO

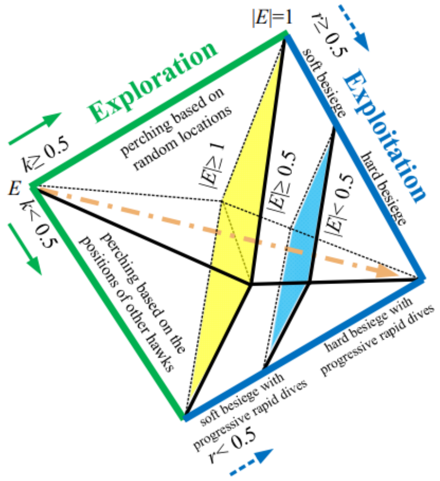

Figure 5. Various exploration phases of HHO

6. PROPOSED OPTIMAL CONTROLLER FOR AUTONOMOUS MICRO GRID

In is paper optimal control of autonomous micro grids is presented. In the voltage controller and current controller gain values are tuned by optimization techniques. In this paper PSO and HHO optimization techniques are implemented to obtain the optimal gain values. To obtain the gain values integral time absolute error (ITAE) of the voltage and current controller are considered by using (3).

$$ITAE = \int_0^t t|e(t)|dt \qquad (3)$$

The flowchart for the optimal controller is shown in Figure 6.

In the proposed optimal controller is implemented on voltage controller and current controller. In the voltage controller the error between Vdc_mean and Vdc_ref are given to the optimal algorithm. The fitness function is obtained by calculating ITAE using (1). Based on the fitness function the gain value K_{iv} and K_{pv} are obtained. Similarly, in the current controller the error between IdIq and IdIq_ref are given to the optimal algorithm. The fitness function is obtained by calculating ITAE using (1). Based on the fitness function the gain value K_{ic} and K_{pc} are obtained.

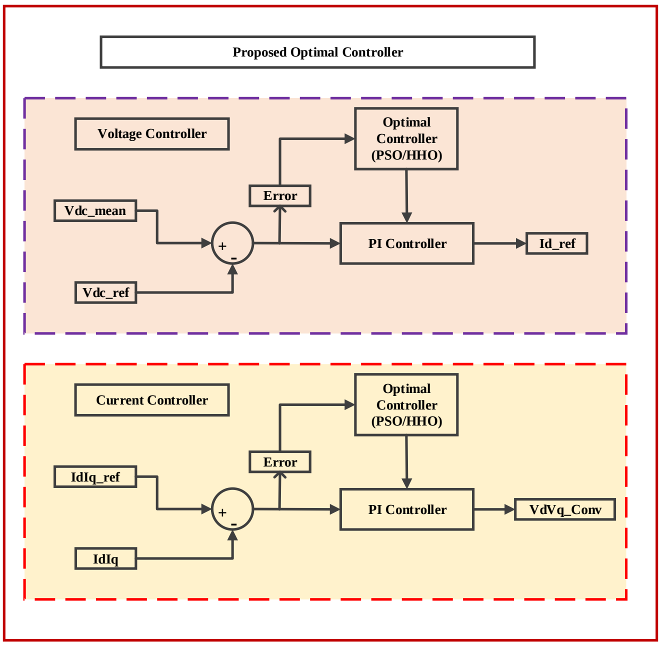

Figure 6. Proposed optimal controller

Test case: in this paper a single phase 3.5 kW PV based autonomous microgrid is considered. The PV array is taken from Trina Solar Manufacturer. The H-bridge type inverter is considered and classic LCL is adopted in this test case as shown in Figure 7. The parameters of the test case are tabulated in Table 1.

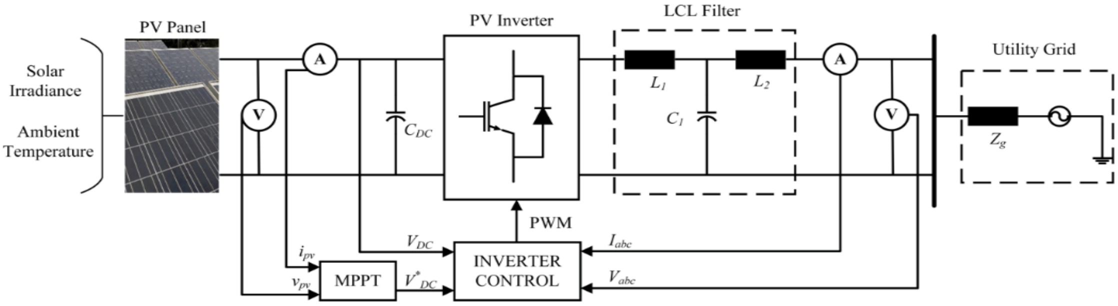

Figure 7. Proposed 3.5 kW PV system

Table 1. Test case parameters

PV array model	TSM-250
Maximum power PV	249.86 W
Voc	37.6 V
Isc	8.55 A
DC link capacitance	3000e-6 F
Capacitor initial voltage	425 V
Ls	2.183 mH
Cs	525 var
RMS voltage	240 V

7. RESULTS AND DISCUSSION

In this paper optimal control strategy of autonomous microgrid for power quality improvement is presented. A test case of single phase 3.5 kW PV system based autonomous micro grid is considered. PSO and HHO optimal control strategies are implemented under standard test case and variable test cases. The optimal control of autonomous microgrid is implemented under the following cases:

- Optimal control of autonomous microgrid using PSO algorithm under standard test conditions.
- Optimal control of autonomous microgrid using PSO algorithm under variable test conditions.
- Optimal control of autonomous microgrid using HHO algorithm under standard test conditions.
- Optimal control of autonomous microgrid using HHO algorithm under variable test conditions.

7.1. Optimal control of autonomous microgrid using PSO algorithm under standard test conditions

In this case PSO algorithm is implemented on single phase 3.5 kW PV system based autonomous microgrid under the standard test conditions i.e., solar irradiance is 1000 w/m^2 and ambient temperature is 25 °C as shown in Figure 8. The PSO algorithm is initialized with the following parameters:

- Swarm size is 50.
- constant C1 is 0.5 Constant C2 is 1.25.
- Inertia weight W is 1.
- Maximum velocity V is 10.
- Number of iteration are 200.

The gain values obtained for voltage controller are Kpv is 1.5016, Kiv is 3.2419, similarly the gain values obtained for current controller are Kpc is 0.6277, Kic is 3.5928. Under the standard test condition PV mean voltage (Vmpv) obtained is 433.8 V, PV mean current (Impv) obtained is 8.05 A, as shown in Figure 9. The PV mean power (Pmpv) obtained is 3492.09 W. The autonomous microgrid rms voltage (Vrms) obtained is 239 V, rms current (Irms) obtained is 14.41 A, as shown in Figure 10 the autonomous grid power (Pg) obtained is 3433.99 W. The THD analysis with PSO optimal controller based autonomous microgrid under standard test conditions is recorded as 3.22% percentage as shown in Figure 11. The PSO optimal controller obtains the PV inverter efficiency of 98.62%.

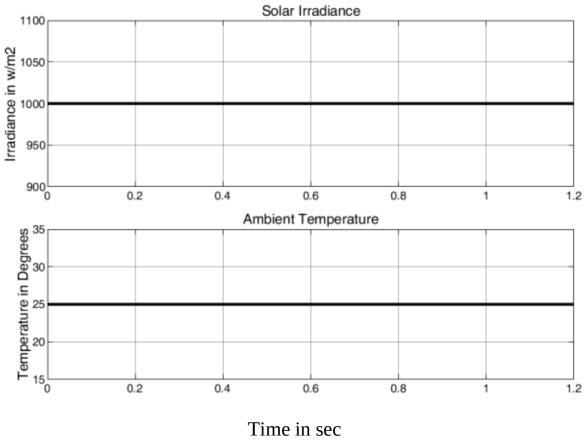

Figure 8. Solar irradiance and ambient temperature under standard test case

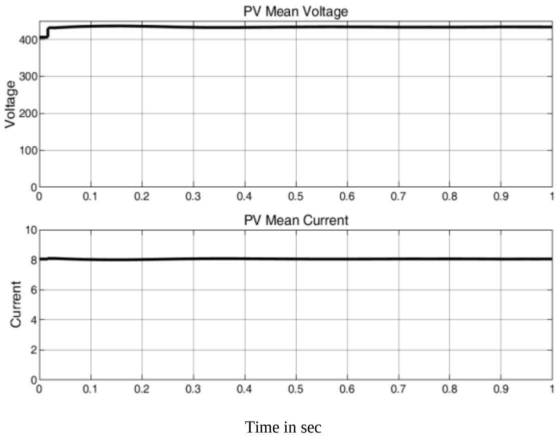

Figure 9. Mean PV voltage and current

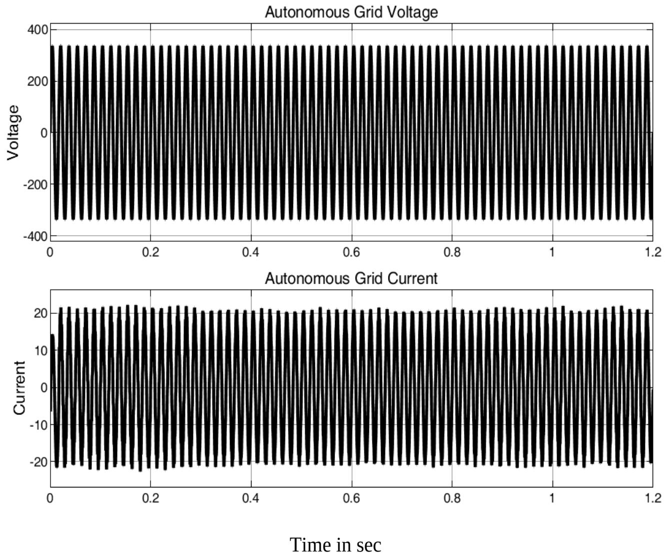

Figure 10. Autonomous grid voltage and current

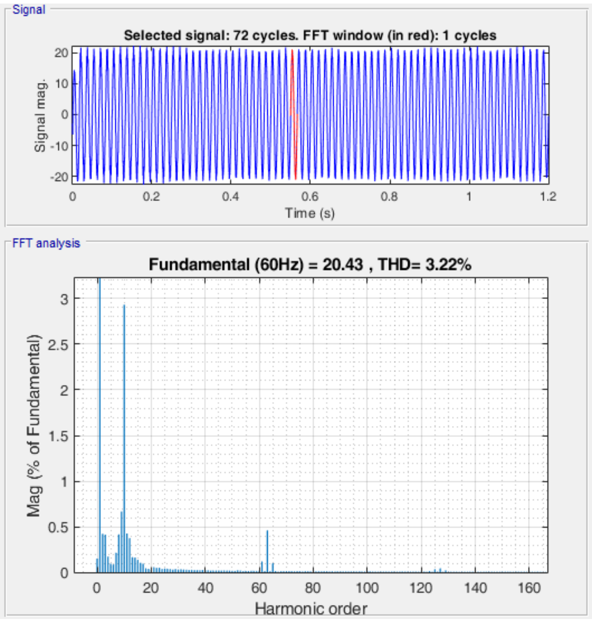

Figure 11. THD analysis with PSO controller under standard test conditions

7.2. Optimal control of autonomous microgrid using PSO algorithm under variable test conditions

In this case PSO algorithm is implemented on single phase 3.5 kW PV system based autonomous microgrid under the variable test conditions i.e., at time period 0 s, 0.9 s solar irradiance is 1000 w/m^2, 800 w/m^2 and ambient temperature is 25 °C, 35 °C respectively as shown in Figure 12. In the PSO algorithm swarm size is 50, constant C1 is 0.5, C2 is 1.25, inertia weight W is 1, maximum velocity V is 10, number of iteration are 200. The gain values obtained for voltage controller are Kpv is 1.5016, Kiv is 3.2419, similarly the gain values obtained for current controller are Kpc is 0.6277, Kic is 3.5928.

Under the variable test condition PV mean voltage (Vmpv) obtained is 401.5 V, PV mean current (Impv) obtained is 6.624 A, as shown in Figure 13. The PV mean power (Pmpv) obtained is 2659.536 W. The autonomous microgrid rms voltage (Vrms) obtained is 238.9 V, rms current (Irms) obtained is 10.27 A, as shown in Figure 14. The autonomous grid power (Pg) obtained is 2453.503 W. The THD analysis with PSO optimal controller based autonomous microgrid under standard test conditions is recorded as 3.22% percentage as shown in Figure 15. The PSO optimal controller obtains the PV inverter efficiency of 92.25%.

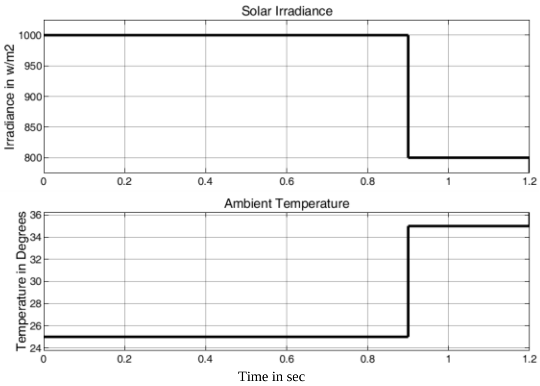

Figure 12. Solar irradiance and ambient temperature under variable test case

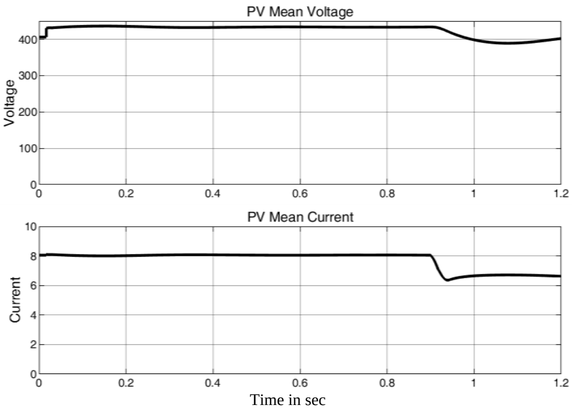

Figure 13. Mean PV voltage and current

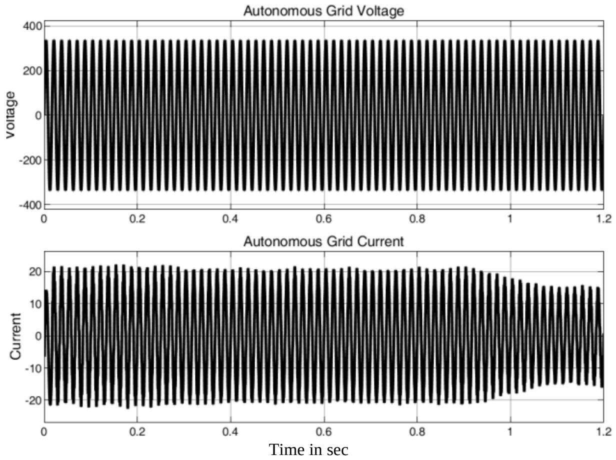

Figure 14. Autonomous grid voltage and current

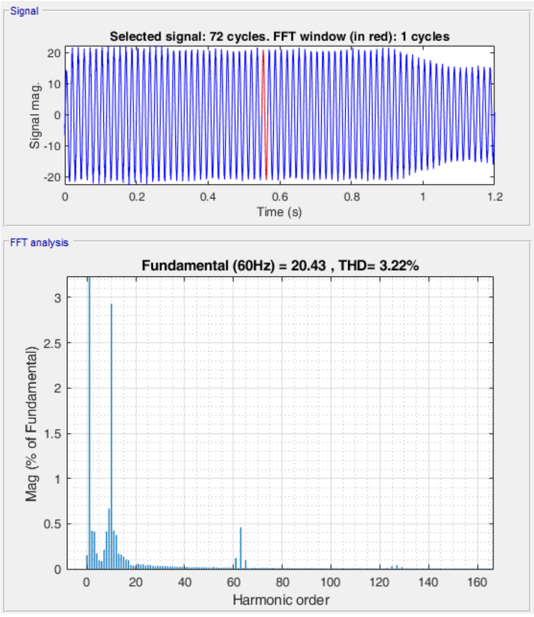

Figure 15. THD analysis with PSO controller under variable test conditions

7.3. Optimal control of autonomous microgrid using HHO algorithm under standard test conditions

In this case HHO algorithm is implemented on single phase 3.5 kW PV system based autonomous microgrid under the standard test conditions i.e., solar irradiance is 1000 w/m^2 and ambient temperature is 25 ℃ as shown in Figure 16. The HHO algorithm is initialized with the following parameters:

- Hawks size is 30.
- Random generation r1, r2, r3, r4 ranges from 0 to 1.
- Number of search agents are 7.
- Convergence probability r is 0.5.
- Number of iterations are 200.

The gain values obtained for voltage controller are Kpv is 1.5104, Kiv is 3.2812, similarly the gain values obtained for current controller are Kpc is 0.5916, Kic is 3.5896. Under the standard test condition PV mean voltage (Vmpv) obtained is 433.8 V, PV mean current (Impv) obtained is 8.05 A, as shown in Figure 17. The PV mean power (Pmpv) obtained is 3492.09 W. The autonomous microgrid rms voltage (Vrms) obtained is 239 V, rms current (Irms) obtained is 14.47 A, as shown in Figure 18. The autonomous grid power (Pg) obtained is 3458.33 W. The THD analysis with HHO optimal controller based autonomous microgrid under standard test conditions is recorded as 2.31% percentage as shown in Figure 19. The HHO optimal controller obtains the PV inverter efficiency of 99.03%.

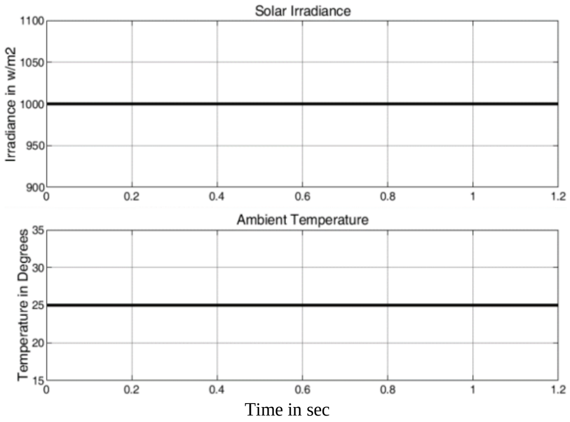

Figure 16. Solar irradiance and ambient temperature under standard test case

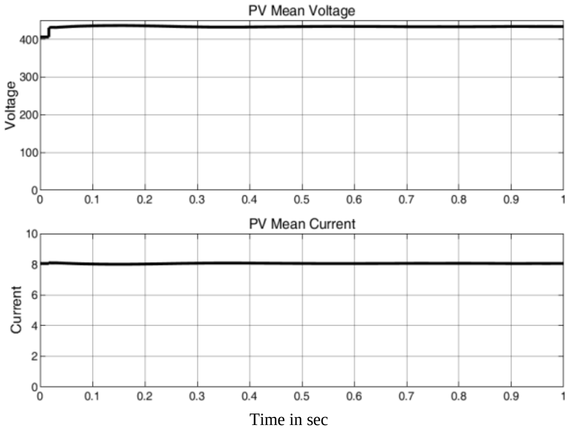

Figure 17. Mean PV voltage and current

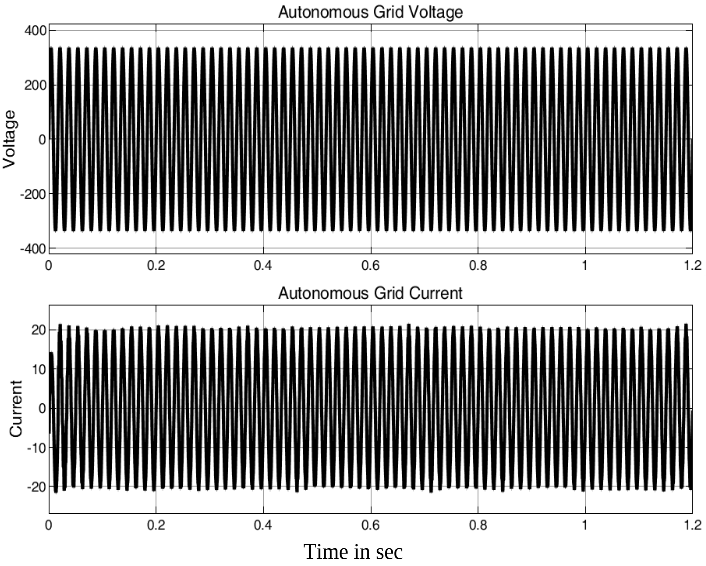

Figure 18. Autonomous grid voltage and current

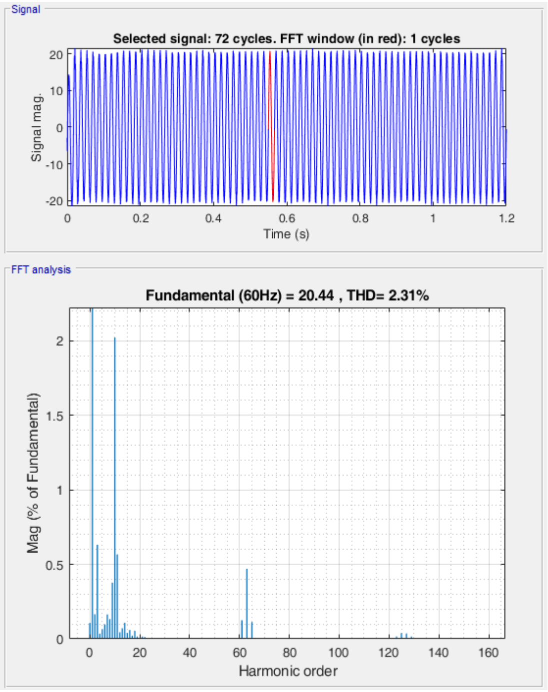

Figure 19. THD analysis with HHO controller under standard test conditions

7.4. Optimal control of autonomous microgrid using HHO algorithm under variable test conditions

In this case HHO algorithm is implemented on single phase 3.5 kW PV system based autonomous microgrid under the variable test conditions i.e., at time period 0 s, 0.9 s, solar irradiance is 1000 w/m^2, 800 w/m^2 and ambient temperature is 25 °C, 35 °C respectively as shown in Figure 20. In the HHO algorithm hawks size is 30, random generation r1, r2, r3, r4 ranges from 0 to 1, number of search agents are 7, convergence probability r is 0.5, number of iterations are 200. The gain values obtained for voltage controller are Kpv is 1.5104, Kiv is 3.2812, similarly the gain values obtained for current controller are Kpc is 0.5916, Kic is 3.5896.

Under the variable test condition PV mean voltage (Vmpv) obtained is 401.5 V, PV mean current (Impv) obtained is 6.624 A, as shown in Figure 21. The PV mean power (Pmpv) obtained is 2659.536 W. The autonomous microgrid rms voltage (Vrms) obtained is 238.9 V, rms current (Irms) obtained is 10.31 A, as shown in Figure 22. The autonomous grid power (Pg) obtained is 2463.059 W. The THD analysis with HHO optimal controller based autonomous microgrid under standard test conditions is recorded as 2.31% percentage as shown in Figure 23. The HHO optimal controller obtains the PV inverter efficiency of 92.61%.

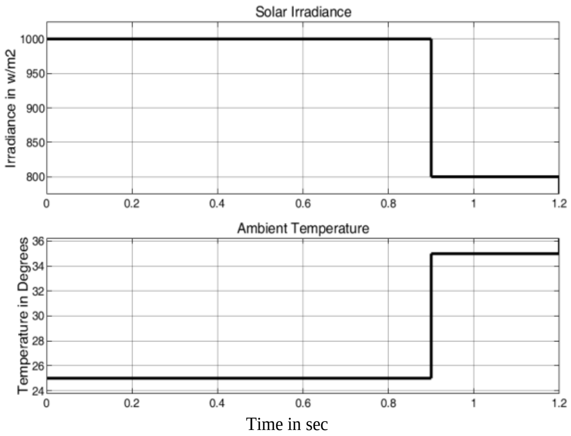

Figure 20. Solar irradiance and ambient temperature under variable test case

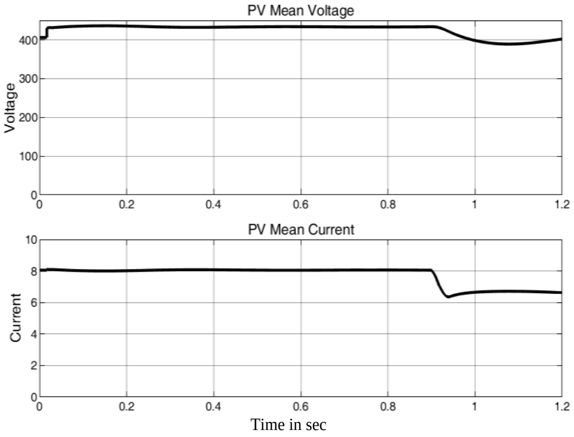

Figure 21. Mean PV voltage and current

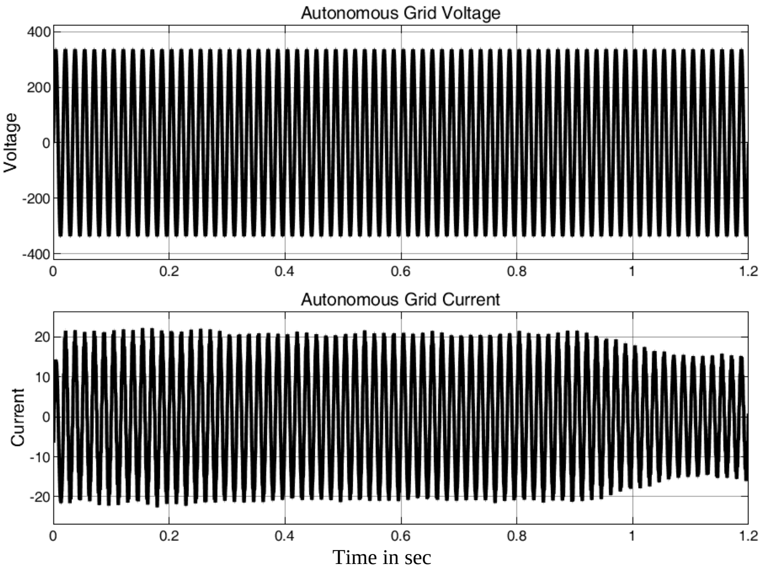

Figure 22. Autonomous grid voltage and current

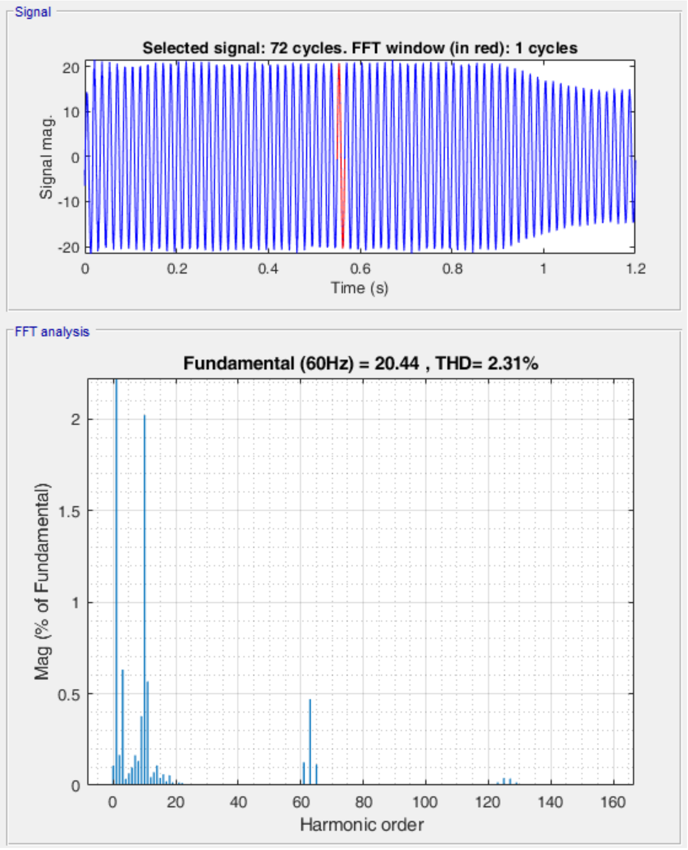

Figure 23. THD analysis with PSO controller under variable test conditions

7.5. Comparison analysis

In the PSO and HHO optimal control strategies are implemented. The HHO optimal control strategy for autonomous microgrid exhibits the best performance in comparison with PSO optimal control strategy. The THD is reduced from 3.21% to 2.31%. The detailed comparison analysis of standard test conditions (STC) and variable test conditions (VTC) shown in Table 2.

Table 2. Comparison analysis

Algorithm	Test condition	Ppv (W)	Pg (W)	Efficiency %	THD %	Inverter losses %
PSO	STC	3492.09	3443.99	98.6226	3.22	1.377399
	VTC	2659.536	2453.503	92.25305	3.22	7.746953
HHO	STC	3492.09	3458.33	99.03324	2.31	0.966756
	VTC	2659.536	2463.059	92.61236	2.31	7.387642

8. CONCLUSION

In this paper a test case of single phase 3.5 kW PV system based autonomous micro grid is considered. Optimal control strategy of autonomous microgrid for power quality improvement is presented. In this paper PSO and HHO optimal algorithms are considered and compared. Both PSO and HHO optimal control strategies are considered under standard test case and variable test case. In the standard test conditions solar irradiance is 1000 w/m2 and ambient temperature is 25 ℃. In the Variable test conditions at time period 0 s, 0.9 s, solar irradiance is 1000 w/m2, 800 w/m2 and ambient temperature is 25 ℃, 35 ℃ respectively. In all the cases Vmpv (V), Impv (A), Vrms (V), Irms (A), Ppv (W), Pg (W), efficiency (%), THD (%), inverter losses (%) are evaluated. In all the cases HHO optimal control strategy for autonomous microgrid exhibits the best performance in comparison with PSO optimal control strategy. The inverter efficiency is improved, inverter losses are decreased and the THD is reduced from 3.21% to 2.31%.

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