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Design of an Optimized Pi Controller Converter for Integrating Renewable Sources to Grid System

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ABSTRACT
A great technical concern of synchronization is presently raised by the recent integration of converter interfaced generators into the convention grid. While there are various control techniques, a Phase-Locked Loop (PLL) is required in synchronizing power inverters output signal and that of the grid. In this research work, the optimal tuning of PLL structure PI- parameters is carried out using metaheuristic algorithm as against manual tuning technique. Dandelion optimization (DO) Algorithm was applied in the PI-PLL tuning under the ITAE and IAE error criteria. The performance of Dandelion Optimizer was compared to that of Particle Swarm Optimization (PSO) for comparison and the result obtained showed that Dandelion Optimizer evaluated with the Integral Time Absolute Error (ITAE) obtained PI parameters that achieved a faster settling of 5.72ms as compared to PSO with a settling time of 7.74ms.

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I. INTRODUCTION

It is universally agreed that human development is impossible without a reliable and sustainable energy supply [1]. The continual expansion in global population, fast urbanization, and enormous rise in technical complexity and advancements are all contributing to the astounding growth in the demand for electric power on a global scale. According to statistics, between 2005 and 2030, the world's energy consumption is expected to rise by nearly 55 percent [2], [3].

Presently, the power system landscape is taking a new shape as renewable energy portfolio standards, particularly that of solar and wind are continually evaluated and streamlined for reliable renewable energy integration into the existing grid power grid. For over a decade, there are growing operational variances and concerns about the overall power system's ability to operate reliably and securely as a result of the rapid uptake of renewable energy sources in the electrical power system [4].

This development raises many concerns regarding power stability as both the steady state and transient stability of the system are stretched. Thus, adjusting the power flow of such renewable producing units in response to the system oscillations, the chaos brought on by the increased renewable power penetration or other perturbations can be significantly reduced [1], [5].

Due to the need for grid-tied inverters for a successful integration, the majority of renewable energy grid-connected systems are Converter Interfaced Generators (CIG). However, converter-driven synchronization instability is a common problem for CIG, while grid-related disturbances including voltage sags, harmonics, and frequency variations pose a serious threat to dependable synchronization [5]. Verily, synchronization is a well-established process for connecting an AC source to the power grid. However, if the incoming (plugged-in) inverter (source) is also required to contribute to voltage and frequency restrictions, as well as power-sharing, particularly in low inertia micro-grids, it becomes a technological difficulty [6].

II. REVIEW OF FUNDAMENTAL CONCEPTS

2.1 Power Inverter Classifications

Power inverters are essential components of advanced power systems. They execute the necessary DC–AC inversion, which is crucial to grid synchronization [1]. Regarding their commutation process, they are divided into two categories: Self commutation inverters (SCI) and line commutation inverters (LCI). Thus, they can also be classified as Current Source Inverters (CSI) and Voltage Source Inverters (VSI). Figure 1 provides a detailed explanation of the various taxonomy trees used to categorize inverters [9].

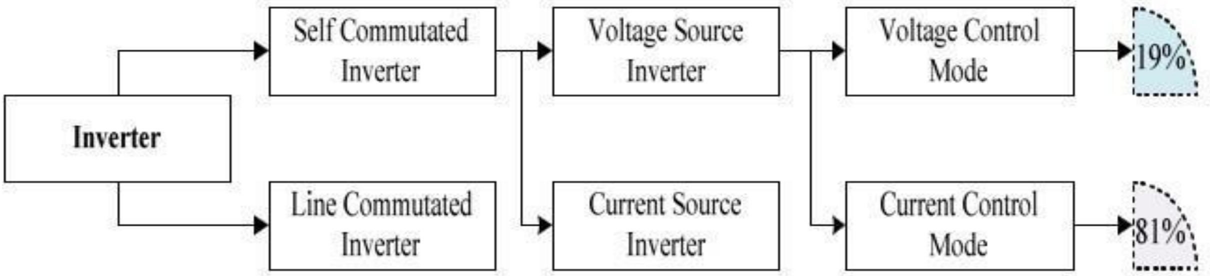


Figure 1: Power Inverter Classifications

2.2 Line Commutated Inverters (LCI)

LCIs are utilized as switches; they are semi-controlled semiconductor devices like thyristors. In these semi- controlled switching devices, the gate terminal controls the ON operation, while the circuit parameters that is, the polarity of the current or voltage determine the OFF properties of the switches. A forced commutation is required to turn OFF the switches in LCI, based on this requirement different approaches are presented [10].

2.3 Self Commutated Inverter

In series compensation, a dynamic voltage restorer (DVR) operates. It is made up of a voltage source inverter that is connected in series with the supply line to help achieve a specific load voltage. When VSI is conducted using an external DC voltage source, the DVR can be employed for voltage harmonic compensation, load voltage management, and voltage imbalance compensation. [2].

2.4 Current Source Inverter

In Self-Commutated Inverter, MOSFET or IGBT devices are typically utilized. MOSFETs are used for high frequency (20–800 kHz) applications having power ratings less than 20 kW. In contrast, low frequency (20 kHz) applications with power ratings higher than 100 kW employ IGBTs. The gate terminal provides complete control over the commutation operations of these switches [11]. As a result, it regulates the output waveforms for both current and voltage. In grid-connected applications, high switching frequency devices are preferred because they lower the weight of the inverter, the size of the filter, and the output waveform harmonics [12]. Moreover, SCI improves the grid power factor, suppresses the current harmonics, and shows high robustness to the grid disturbances. As opposed to LCI, SCIs are preferred due to the advancement of advanced switching devices and better control procedures. The SCIs are further classified into current source inverter (CSI) and voltage source inverter (VSI).

2.5 Current Source Inverter

In CSI, a DC current source is connected as an input to the inverter; hence, the input current polarity remains the same. Consequently, the polarity of the input DC voltage determines the direction of power flow. The current waveforms acquired at the CSI output side exhibit changing width but constant amplitude. To address the current stability issue, the primary drawback of CSI is the use of a large inductor coupled in series with the input side [13]. The circuitry becomes less effective, large, and costly when an inductor is used [14].

2.6 Voltage Source Inverter

A DC voltage source is connected as an input to the VSI, hence the input voltage polarity remains the same. Consequently, the direction of power flow is determined by the direction of input current. An output AC voltage's waveforms vary in width but remain constant in amplitude. Furthermore, using a big capacitor connected in parallel with the input source is a significant disadvantage of VSI [13]. Compared to CSIs, VSIs are preferred for usage in grid-tied PV applications because of their low power losses, high efficiency, affordability, and lightweight nature. Moreover, VSIs are operated in either VCM or CCM mode according to their control mode.

III. CONTROL STRATEGIES OF GRID CONNECTED POWER INVERTERS

A PV power system is a power-electronics based system, their control plays a very significant functions in the smooth and stable operation of the power system. If there is no robust and suitable controller designed, the inverter will cause grid instability and disturbances in the system. Based on grid behaviour and operating conditions, controllers are divided into linear, predictive, robust, non-linear, adaptive, and intelligent controllers as shown in Figure 2 [15].

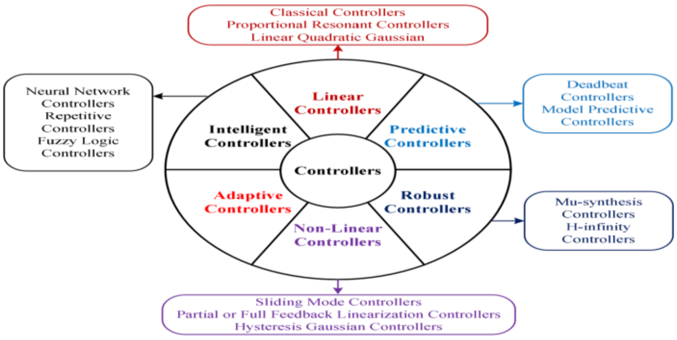


Figure 2: Different Types of Control Strategies

IV. GRID TIED INVERTER CONTROL STRATEGIES

The control strategy used for the grid-tied inverter is classified into a single loop, double loop, and triple loop systems**.**

4.1 Single Loop Control System

This is a control loop system applied in applications requiring the regulation of only one variable (current or voltage). In current regulations, it produces good power flow regulation and harmonic rejection. However, a single sensor is used to protect the inverter from over-current [16]. For voltage regulation, this control structure does not offer any protection from the short circuit or resonance damping; therefore, an additional prerequisite is needed to improve the system reliability and stability [17]. The structure of a single loop is presented in Figure 3 where HS presents the applied regulator.

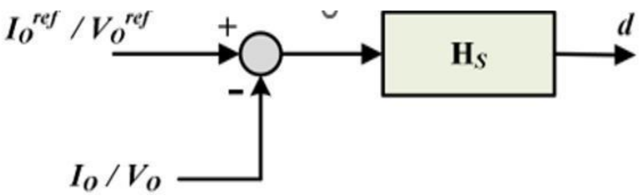


Figure 3: Single Loop with H_S Regulator

4.2 Double Loop Structure

A double loop structure is a control loop in which two loops that is cascaded over one another and is used to regulate two variables. Issues like protection of devices from the current and power quality enhancement are related to the current loop. The HD1 is a slow external voltage loop that regulates the voltage at the DC-link [14]. However, for stability purpose, the dynamic speed of an outer loop must be 5–20 times slower than the inner loop [18]. Instead of the cascade of current and voltage control loops, the cascade of power and voltage loops can also be used, and the grid injected current is controlled indirectly. Figure 4 represents a double loop with H_{D1} and H_{D2} are the outer and inner loop regulators respectively.

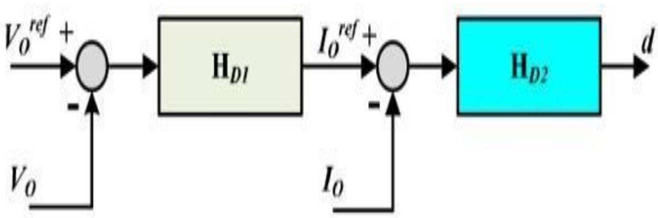


Figure 4: Double loop with Inner (H_{D1}) and Outer (H_{D2}) loop regulators

4.3 Triple Loop Structure

A triple loop control is the most modern structure presented in the literature [19], [20] and is implemented in a cascaded manner as presented in Figure 5, where H_{T1}, H_{T2}, and H_{T3} are the applied regulators. The implementation and analysis of this structure is more complex than the single or double structures, as every loop bandwidth is limited by the response delay of the inner loop. Therefore, it is very difficult to attain width bandwidths for the most outer loop. Among the control loop structures, a triple loop structure provides more control flexibility and makes it more beneficial for the high performance of the grid-connected inverters.

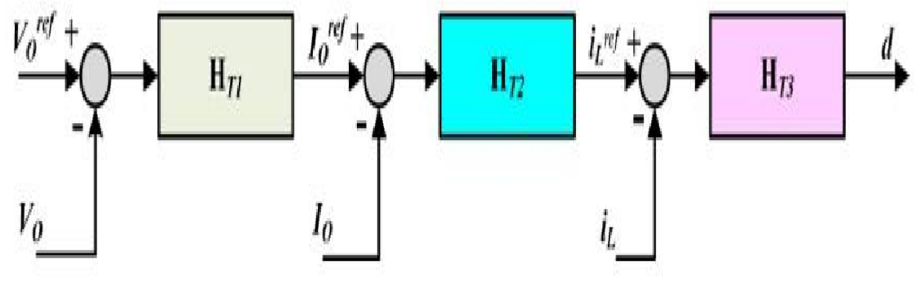


Figure 5: Triple Loop Structure

V. CONTROLLERS REFERENCE FRAMES

For controlling the grid-tied inverter three reference frames (*dq*, αβ, and *abc*) are used, that are discussed below;

5.1 *abc* Reference Frame

An *abc* reference frame as shown in Figure 6 is applied to 3-Φ systems without any transformation and for each grid current a separate controller is utilized, but the delta or star connections must be in consideration while designing a controller [21]. Numerous regulators are applied in double loop structures such as P-proportional resonant (PR) P- PI, PI-PR, deadbeat (DB)-PI and hysteresis current control (HCC)-PR [22], [23]. Due to fast dynamic response, simple transfer function, lack of requirement for the modulator, and fast development the controller such as deadbeat and hysteresis are preferably used in *abc* reference frame [24]. Moreover, the PI transfer function in *abc* frame becomes more complex and causes an increment in the overall system complexity. The transfer function of PR is simple as compared to PI controller but more complex than the deadbeat and hysteresis controller.

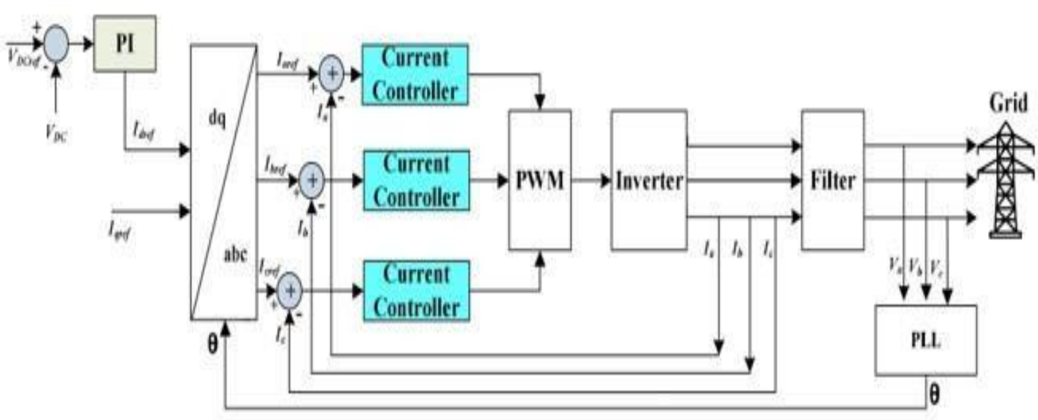


Figure 6: abc Reference Frame

5.2 dq Reference Frame

In this reference frame, the current and voltage in *abc* frame are converted into synchronous current components (I_d and I_q) and voltage components (V_d and V_q) into *dq* frame using a Park transformation. It converts the grid voltage and current into a reference system in which they revolve continuously with the grid voltage. By using this approach, the controls variables are converted from the sinusoidal domain are transformed into DC domain which can easily be controlled and filtered [25]. In the last few years, numerous controllers are applied in a single loop structure such as proportional-integral (PI) proportional (P) dead-beat (DB) proportional-resonant (PR) in which the PR shows a prominent performance [19], [26], [27]. PI is usually used in *dq* reference frame in GCPPPs due to its simple configuration, uncomplicated control, and easy filtering. A generalized configuration of proportional integral (PI) applied in *dq* reference frame is presented in Figure 7.

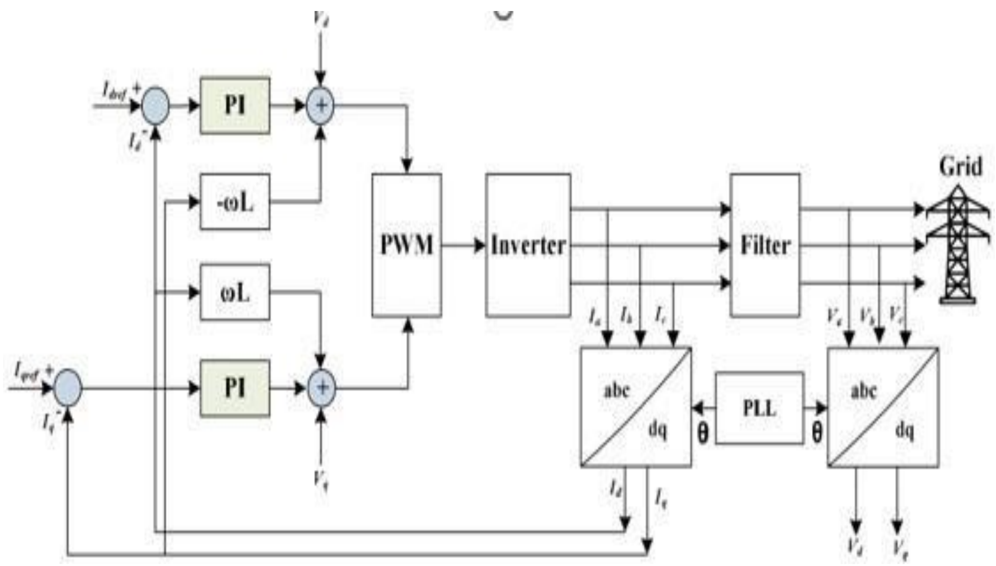


Figure 7: dq Reference Frame

VI. PHASE LOCKED LOOP

The words PLL means “Phase- Locked Loop”, PLL is a control system that generates an output signal whose phase is related to the phase of an input signal. While there are several differing types, it is easy to initially visualize as an electronic circuit consisting of a variable frequency oscillator and a phase detector. The oscillator generates a periodic signal, and the phase detector compares the phase of that signal with the phase of the input periodic signal, adjusting the oscillator to keep the phases matched. Bringing the output signal back toward the input signal for comparison is called a feedback loop since the output is "fed back" toward the input forming a loop.

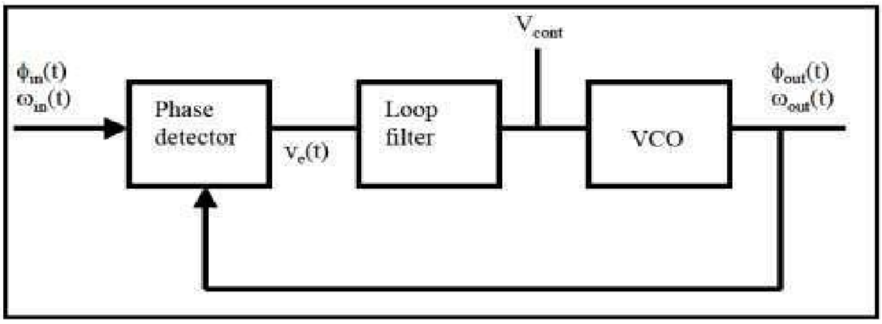


Figure 8: Phase Lock Loop Structure

A PLL is a feedback system that includes a VCO, phase detector, and low pass filter within its loop. Its purpose is to force the VCO to replicate and track the frequency and phase at the input when in lock. The PLL is a control system allowing one oscillator to track with another. It is possible to have a phase offset between input and output, but when locked, the frequencies must exactly track [28]. Some of the major benefits of phase locked loop include the following;

- Eliminates the problem of frequency drift.
- Increase battery life of product
- Less manufacturing cost
- PLL System is very important in generating accurate and stable frequency.

VII. PI CONTROLLER

PI and PID controllers are the most popular controllers used in industry because of their simplicity, robustness, a wide range of applicability and near-optimal performance. A survey has shown that 90% of control loops are of PI or PID structure. Good awareness of design and tuning methods is increasing important to both users and designers. A PID design procedure should include these three aspects: process model identification, controller structure design and PID parameters tuning [29], [30], [31] PID parameter tuning is a core part of the controller design. The model identification lay the foundation for parameters tuning and the controller structure design decouple set-point following and load disturbance rejection [31].

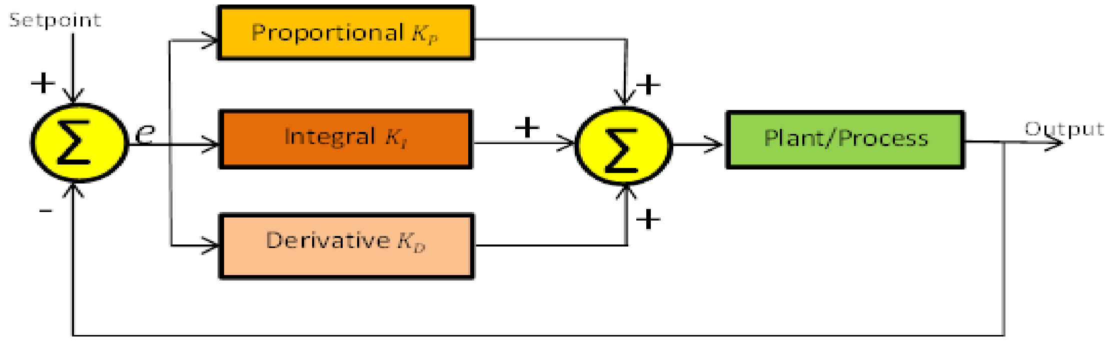


Figure 9: PID Controller Block Diagram [31]

VIII. METAHEURISTIC OPTIMIZATION

Conventional and classical optimization methods are not efficient enough to deal with complicated, NP-hard, high- dimensional, non-linear, and hybrid problems. In recent years, the application of meta-heuristic algorithms for such problems increased dramatically and it is widely used in various fields [32]. These algorithms, in contrast to exact optimization methods, find the solutions which are very close to the global optimum solution as possible, in such a way that this solution satisfies the threshold constraint with an acceptable level.

Meta-heuristic algorithms which are a way to solve optimization problems start by generating random response (s) then move forward toward optimizing based on their operators and through changing the created random answers [33], [34] In general, all meta-heuristic algorithms use the similar mechanism to find the optimal solution. In most of these algorithms, the search starts by generating one or more random solutions in an acceptable range of variables. The primary generated solution in population-based algorithms is called population, colony, group, etc. and also each of solutions is called chromosome, particle, ant, and etc. Then, using operators and various methods of combining primary solutions, new solutions are generated. Moreover, the new solution will be chosen from the previous ones, and this process will continue until the stop criterion is met [34].

8.1 Dandelion Optimizer

A dandelion algorithm (DA) was proposed in 2017 as a kind of swarm intelligence algorithm inspired by the behaviour of dandelion sowing. X. Li, S. Han, L. Zhao, C. Gong, and X. Liu, “New dandelion algorithm optimizes extreme learning machine for biomedical classification problems,” Computational intelligence and neuroscience, 2017. [35] DA establishes a mathematical model by simulating the behaviour of dandelion sowing, and uses a parallel search method by introducing random factors and selection strategies. It is capable of solving complex problems. It is similar to a general swarm intelligence optimization algorithm. Firstly, N dandelions are randomly initialized. Then, each dandelion undergoes normal sowing and mutation one, respectively. Finally, the best dandelion is retained, and then a selection strategy is used to select N-1 from the remaining dandelions, which forms a new population with the best dandelion for the next iteration. The algorithm ends when the optimal location is obtained.

In DA, mutation sowing using Levy mutation is important. It can make DA jump out of local optima since Levy mutation leads to strong global search ability. Therefore, DA has the ability of exploration. However, a competitive intelligent algorithm should also have the ability of exploitation. Dandelion Algorithm with Probability-based Mutation [35].

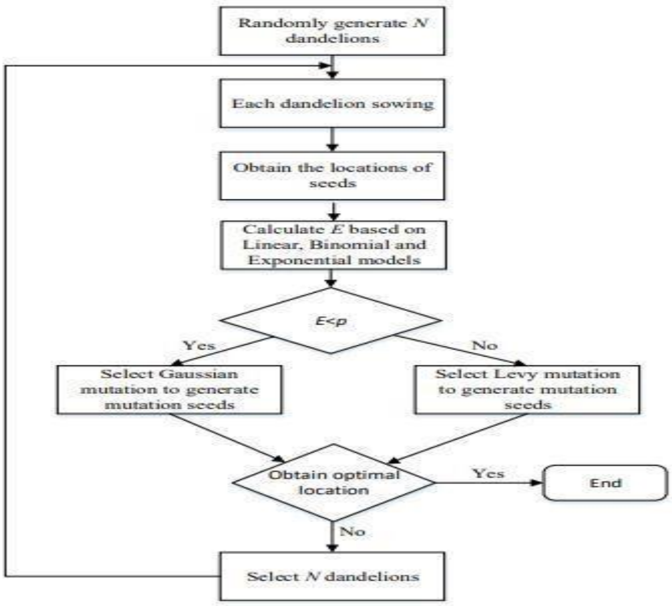


Figure 10: Dandelion Optimizer Flow Chart

8.2 Particle Swarm optimization

For solving optimization issues, one popular population-based metaheuristic approach is particle swarm optimization (PSO). It mimics how birds in a flock interact with one another in order to reach their feeding objective. A flock of birds uses both their individual and group social experiences to approach their food source. They continuously adjust their position based on their own and the swarm's optimal positions, rearranging themselves into the best arrangement possible [31], [36]. Russell Elberhart, an electrical engineer, and James Kennedy, a social psychologist, were motivated to use the social interaction principle in problem solving by the social psychological behaviour of birds. [36], [37]. Generally, PSO algorithm utilizes iterations and is based on swarm intelligence in nature. The process commences with a group of potential solutions, referred to as a swarm [36].

IX. METHODS OF THE STUDY

A step-by-step modelling approach of the various parts of the grid-tied power inverter is adopted in carrying out this study. A general model of the inverter to grid synchronization adopted in this study is as shown in Figure 11.

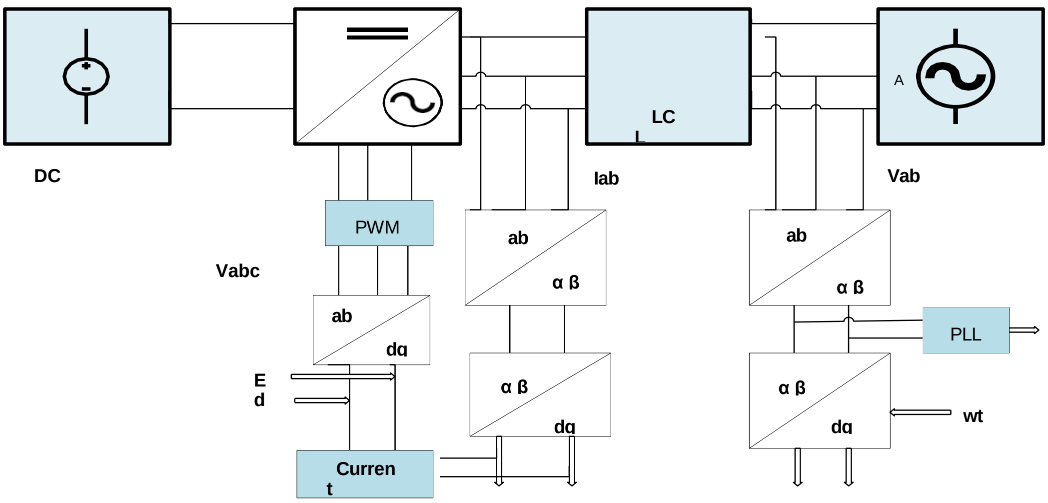


Figure 11: Grid-connected inverter with Phase Locked Loop Control.

The respective fundamental mathematical relationships considered for the modelling are presented in this sub-section.

9.1 Design of Three Phase Inverter and Its Control

The inverter inner controller operation requires direct-quadrature (d-q) transformation as its control works with the d-q model. The MATLAB implementation of the three phase inverter used for the study is as shown in Figure 12.

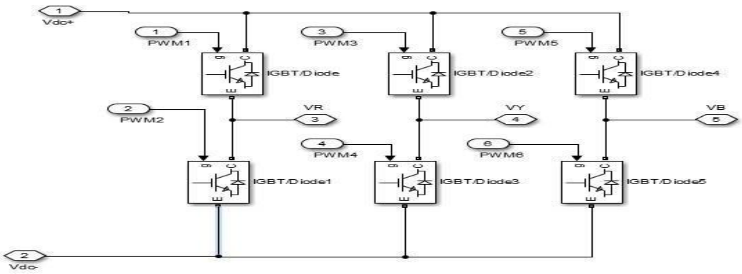


Figure 12: MATLAB Implementation of Three Phase Inverter

Hence, establishing the desired synchronization of grid's current signal and voltage to that of the grid-tied inverter requires the transformation of the three-phase voltage and current signal from the grid to their d-q equivalent (abc to dq transformation). This transformation to the d-q axes references frames are represented in Equations 1 and 2 [38].

$$\begin{pmatrix} V_{od} \\ V_{oq} \\ V_o \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} V_{gr} \\ V_{gy} \\ V_{gb} \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} I_{od} \\ I_{oq} \\ I_o \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} I_{gr} \\ I_{gy} \\ I_{gb} \end{pmatrix} \tag{2}$$

Where V_{od}, I_{od} and V_{oq}, I_{oq} are the voltage and current in the d–q axis reference frames, respectively, (V_{ga}, V_{gb}, and V_{gc}) , (I_{gr}, I_{gy}, and I_{gb}) and are the three-phase voltage and current of the grid, respectively.
Accordingly, the real and reactive power (P and Q), which are described in Equation (3) and Equation (4), can be calculated [39].

$$P = \frac{3}{2}(V_{od} \times i_{od} + V_{oq} \times i_{oq}) \tag{3}$$

$$Q = \frac{3}{2}(V_{od} \times i_{od} - V_{oq} \times i_{oq}) \tag{4}$$

Where V_{od}, I_{od} and V_{oq}, I_{oq} are the voltage and current in the d–q axis reference frames. P and Q are the real and reactive power respectively.
It is required to determine output active and reactive voltage (V_d^* and V_q^*) of the grid inverter in the d-q synchronous frame at the line frequency. This can be evaluated as shown in equation Equations (5) and (6) [39].

$$V_d^* = i_d^* - i_{od}\,(k_{pd} + \frac{k_{id}}{s}) - \omega * L_f * i_{oq} + V_{od} \tag{5}$$

$$V_q^* = i_q^* - i_{od}\,(k_{pq} + \frac{k_{id}}{s}) + \omega * L_f * i_{od} + V_{oq} \tag{6}$$

9.2 Phase-Lock Loop (PLL)

The utility phase angle is accurately and quickly detected by the PLL system in the grid-connected inverter by synchronizing the utility network [38]. The PI controller drives V_{oq} to be zero and the rotation frequency is set as required for the synchronization by minimizing the error. Thus, the angular frequency (ω) and phase angle (θ) are obtained by evaluating the expressions in equations 7 and 8 [40].

$\omega = K_P^{PLL} V_{oq} + K_I^{PLL} \int_0^t V_{oq}\,dt$ (7)

$\theta = \int_0^t w\,dt.$ (8)

A synchronous PLL frame showing its major components is illustrated in Figure 13.

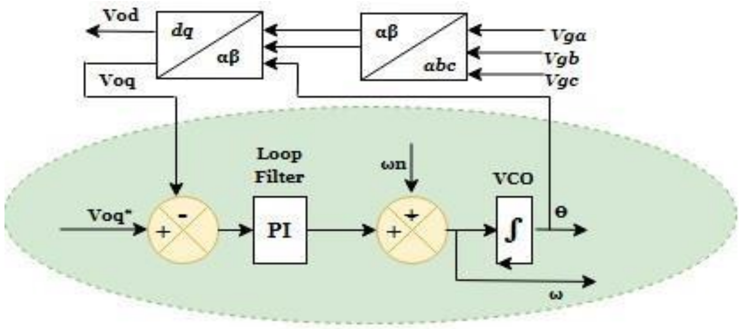


Figure 13: A Synchronous PLL Frame

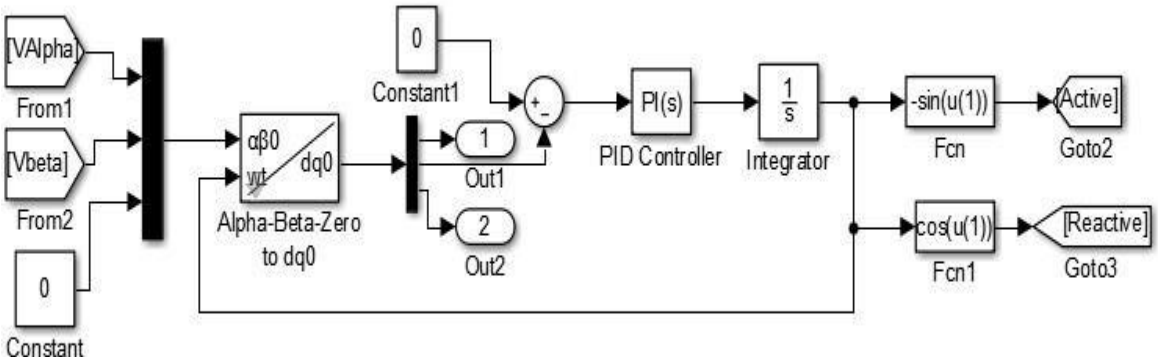


Figure 14: MATLAB SIMULINK Implementation of the PLL

9.3 LCL Filter

A filter is required to ensure that harmonics present in the inverter output current is attenuated before injection into the grid. The current harmonics generated, if injected into the grid, can cause the malfunction of sensitive apparatus connected to the same bus. According to the harmonic standards, that establish the extent of current harmonics introduced into the grid network [5], power filters should attenuate the harmonics to specific levels. Inverters for grid interfacing will need to incorporate interface filters to attenuate the injection of current harmonics.

9.4 Optimization Process

The optimization process is set up to ensure that the Proportional and Integral parameters (PI) parameters of the PLL are well tuned to obtain the desired result. The objective function of the optimization is well defined and evaluated. The optimization parameters for optimizing the PI-PLL parameters was carried out using the dandelion optimizer (DO) and compared to particle swarm Optimizer (PSO) for comparison.

9.5 Optimization Objectives Function

In this study, PI-PLL gains will be optimized through the proposed DO and GA. Minimizing the error (e) between the voltage regulator and current controllers is required and the objective function (J) is evaluated. For critical analysis and ensuring a comprehensive measurement of the controller's performance the minimization is evaluated around the ITAE represented in Equation 9 to Equation 10 [39] .

J_(IAE). = $\int_0^\infty [\,e(t)]^2\,dt$ (9)

J_(ITAE) = $\int_0^\infty t|e|\,dt.$ (10)

Where J is the objective function of the PI controller synchronization problem. The evaluation is aimed to minimize J. Thus, the optimization's constraint is defined by the lower and higher bounds of the optimized parameters. In this case, (K_p^{min} and K_i^{min}) are the lower bounds of the proportional and integral parameters while (K_p^{max} and K_i^{max}) represent the upper bound accordingly.

$$Kpmin \leq Kp \leq Kpmax$$
$$Kimin \leq Ki \leq Kimax$$

9.6 Optimization Parameter Settings

In carrying out the design of PI Phase Lock Loop control scheme for inverter to grid synchronization, some parameters of the optimization techniques need to be properly set. The Parameter Settings used are as presented in Table 1.

Table 1: Parameter Settings for the Optimization Techniques

Parameter	Setting
Population size	200
Number of variables	2
Variables	$Kpll$,$Kipl$,
Iterations	100
Lower boundary	[0, 0]
Upper boundary	[10, 5000]

The two algorithms (DO and GA) used for the analysis were separately set and evaluated 5 times.

9.7 DO Implementation

For implementing the Dandelion optimizer for determining the optimal PI parameters for the PLL, the optimization is set up using the following steps.

Step 1. Initialization
Step 1.1: Constraints setting: The upper and lower limits are set. Step 1.2: Definition of optimization parameters (Kp, Ki)
Step 1.3: Population size is set to 200
Step 1.4: Number of iterations was set to 100
Step 1.5: Objective function definition is defined as (ITAE or IAE)

Step 2: Generating Dandelion Population
N number of dandelions as set in the population size setting is generated. It is confined within the search range as the first-generation dandelion population

Step 3: Sowing
Sowing Process for DA is divided into normal and mutation sowing.
Step 3.1 Normal Sowing: Each dandelion produces dandelion seeds within a certain sowing radius. The number of seeds is calculated based on the fitness value, and the sowing radius is dynamically adjusted
Step 3.2: Mutation Sowing: Levy mutation is used to jump out of a local optimum, and this mutation operation is only for the dandelion with the minimum fitness, which is called the best dandelion.

Step 4: The Best Dandelion:
The best dandelion is always kept in the next generation.
Other N-1 dandelions are chosen from the rest based on a disruptive selection operator.

Step 5: Stopping criterion:
The optimization is terminated if the total number of iterations set in the initialization is reached. Otherwise, the process sowing process.

Step 6: Stopping criterion:
The optimization is terminated if the total number of iterations set in the initialization is reached. Otherwise, the process returns to Step 3.

9.9 PSO Implementation

The implementation of the Particle Swarm Optimization for tunning the PI parameters of the PI-PLL requires the following steps.

Step 1: Initialization
Step 1.1: Constraints setting: The upper and lower limits are set. Step 1.2: Definition of optimization parameters (Kp, Ki)
Step 1.3: Population size is set to 200
Step 1.4: Number of iterations was set to 100
Step 1.5: Objective function definition is defined as (ITAE or IAE)

Step 2: Swarm population creation:
This stage creates the swarm population based on number of variable and constraints. Each swarm flies through the search area using its memory to locate a place that is better than its current one.

Step 3: Production of enhanced swarms.
New swarms are generated as follows through updating swarm velocity and updating swarm position. Step 3.1: Updating swarm velocity
The swarm velocity is an updated using Equation
Step 3.2: Updating the swarm position
The swarm position is also updated

Step 4: Conduct fitness evaluation:
The personal and global best are updated and fitness evaluation is carried out. The desired result (Global best) is obtained.

Step 5: Stopping criterion:
The optimization is terminated if the total number of iterations set in the initialization is reached. Otherwise, the process returns to the update of new velocity and position.

X. RESULTS AND DISCUSSION

At the end of the optimization and all necessary simulations, various results were obtained from which the performance of the designed inverter control techniques was analyzed. The design of an intelligent Dandelion Optimizer (DO)-PI Phase Locked Loop control scheme for a three-phase inverter to grid synchronization power system was also carried out in the study. The DO evaluated with the ITAE error criterion produced the best result as compared to DO-IAE, PSO-ITAE and PSO-IAE for grid tied inverter synchronization.

10.1 Tuning Parameters Result from the Optimization

Optimization of the Phase Lock Loop (PLL) PI parameters for the three-phase inverter to grid synchronization was carried out. The evaluation was conducted over Integral Absolute Error (IAE) and Integral Time Absolute Error (ITAE). To determine the system's optimal PI parameters for the intended inverter-grid synchronization, the PIPLL controller was optimized using Dandelion Optimizer and Particle Swarm optimizer.

Table 2: Tuned PI Parameter based on IAE Error Criterion

Algorithm	PLL-Controller	
	Case (IAE)	
	Kp	Ki .
DO	2.23	2450.9
PSO	1.57	2700.3
	Case (ITAE)	
DO	7.91	4157.8
PSO	3.73	4190.5

The optimization yielded the tuning parameters displayed in Table 2 for the Integral Absolute Error (IAE) and Integral Time Absolute Error (ITAE) case study.

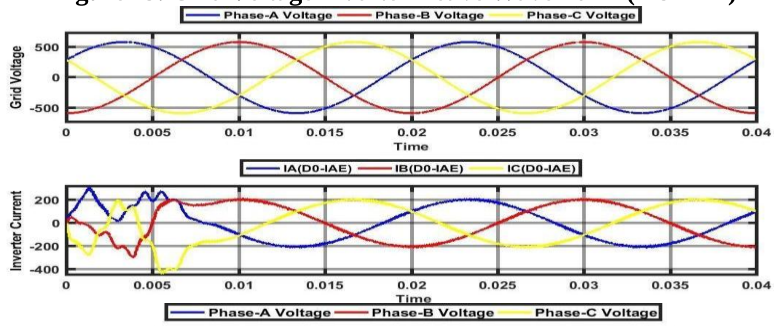
10.2 Simulation Waveforms

The tuned parameters presented in Table 2 were used to simulate the Inverter-AC (grid) power system for synchronization studies. The study examined and compared the performance of PI-PLL based on Dandelion Optimizer (DO) with Particle Swarm (PSO) based designs. For the desired synchronization, the inverter active current is expected to be in phase with the AC (grid) voltage with minimal or no deviations. The more quickly the inverter current waveform settles (settling time), the better the synchronization between the grid-tied inverter synchronization and the AC grid system.

10.3 IAE-Based Active Current Simulation Result

The three-phase inverter-grid power system was simulated using the Integral Absolute Error (IAE) tuned parameters shown in Table 2 to produce the active current waveforms. Figure 15 and 16 show the waveforms for the IAE based studies.

Figure 15: Grid Voltage-inverter Active Wave Form (DO-IEA)



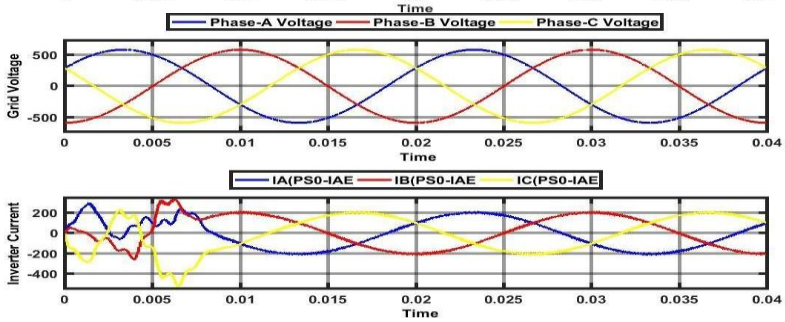


Figure 16: Grid voltage-inverter Active Current Wave Form (PSO-IEA)

10.4 ITAE-Based Active Current Simulation Result

The three-phase inverter-grid power system was simulated using the Integral Absolute Error (ITAE) tuned parameters shown in Table 2 to produce the active current waveforms. Figure 17 and 18 show the waveforms for the ITAE based studies

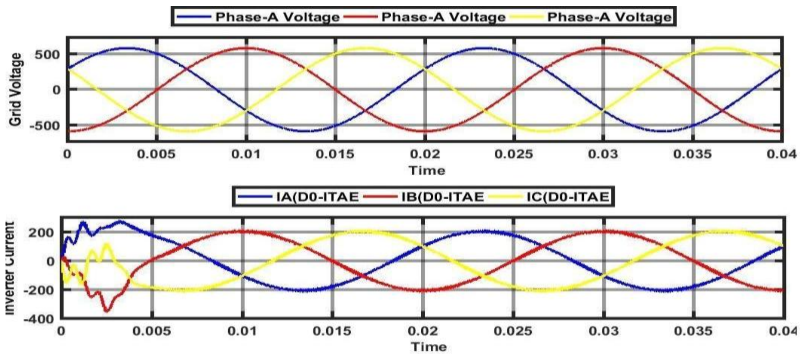


Figure 15: Grid Voltage-inverter Active Wave Form (DO-ITAE)

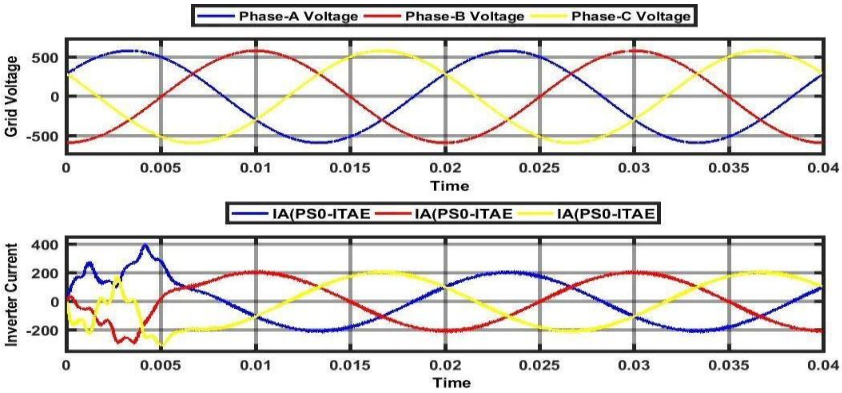


Figure 16: Grid voltage-inverter Active Current Wave Form (PSO-ITAE)

10.5 Inverter Output Current Setting Time

The results of the optimization using Integral Absolute Error (IAE) based and Integral Time Absolute Error (ITAE) metrics for the active current signal settling time are displayed in Table 2. It demonstrates that the suggested DO- optimized PI controller performs noticeably better than the PSO for both case studies. The results indicate that the system with the DO-tuned controller outperforms the PSO optimized controller. For the IAE case study, DO and PSO yielded a maximum settling time of 9.27ms and 9.85ms, respectively. However, the ITAE case study produced a better result. DO and PSO produced a maximum setting time of 6.28 and 7.74 respectively.

Table 3: Active Current Signal Characteristics Result

Optimization Technique	Settling Time (ms)		
	CASE 1: IAE		
	R	Y	B
DO	8.413	9.27	8.99
PSO	8.51	9.66	9.85
	CASE 2: ITAE		
	R	Y	B
DO	6.28	5.72	6.11
PSO	7.55	7.34	7.74

Consequently, it is clear that the suggested Dandelion Optimizer generates an optimal PI parameter for designing the Phase Locked Loop system.

XI. CONCLUSION

A three-phase grid connected power inverter was modelled in MATLAB/SIMULINK environment. The optimization problem of designing a well-tuned Phase Lock Loop stabilizer (PLL) and Inverter current controller structure was technically addressed through the exploration of metaheuristics algorithms. Dandelion Optimizer (DO) was applied for PI parameters tuning obtain the optimal parameters. The performance of the obtained result from the DO is compared to other results obtained from Particle Swarm Optimization (PSO) Hence, the effectiveness of Dandelion Optimizer (DO) based controller in enhancing inverter-grid synchronization was established through the settling time of the nonlinear simulations.

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