# Optimal Fuzzy Sliding Mode Controller Design using Bee Algorithm for Dynamic Voltage Restorer System

**Somporn Tiacharoen**[*1] and **Theerayuth Chatchanayuenyong**[*], Non-members

**ABSTRACT**

This paper proposes an application of the bee algorithm (BA) in order to design an optimal proportional-integral-derivative (PID) controller, a sliding mode (SM) controller, and a fuzzy sliding mode (FSM) controller for a dynamic voltage restorer (DVR) system. The DVR is an electronic device, which has excellent dynamic capabilities and is well suited in protecting critical or sensitive loads from short duration voltage sags or swells. The parameters of the optimal PID, SM, and FSM controllers are automatically tuned by the BA to compensate for the magnitude of load voltage by injecting the compensating voltages when the source voltage sags and swells. In order to confirm these concepts and to show that the proposed strategy outperforms other strategies when it is compared to others using the trial and error method, experimental and simulation setups were implemented in various cases.

**Keywords**: Bee algorithm, Dynamic voltage restorer, Fuzzy logic, Sliding mode control

## 1. INTRODUCTION

In an electrical power system, voltage deviation is problematic for sensitive consumers. Voltage sags and swells are characterized by reductions and increases in voltage. These conditions affect customers [1]. To prevent these effects, advanced electronic power equipment has been developed to ensure a supply of high quality. A dynamic voltage restorer (DVR) is one such custom power device, which has excellent dynamic capabilities. Furthermore, it is well suited to protect critical or sensitive loads from short duration voltage sags or swells [2].

However, the DVR needs to contain an efficient controller in order to manage the load voltage of the system. In the past, classical control and modern control theories have been used to solve such problems in conventional controller design [3], such as proportional-integral-derivative (PID) controllers [4], state feedback controllers, self-tuning controllers, and model reference adaptive controllers [5]. Unfortunately, these approaches require highly accurate mathematical models and a high degree of sensitivity to load disturbances and parameter variations. To avoid the requirement for accurate mathematical models, the sliding mode (SM) controller was introduced [6, 7]. The advantages of SM controller are its “insensitivity” to variations in system parameters, external disturbances, and modelling errors [8, 9]. However, the disadvantage of this control strategy is the large control chattering. To overcome this issue, the sign function is removed from the hitting control law of the SM controller.

In past decades, the use of fuzzy logic (FL) controllers has been proposed in the control system [10]. The advantages of FL are its ease of implementation, high performance, and robustness. At present, much attention is being given to combining the FL and SM, which is referred to as the fuzzy sliding mode (FSM) controller. The advantages of FSM controller are its fast response time, low damping, and reduced chatter. Nevertheless, in the design of the FSM controller, the determination of sliding gain and slope, membership function, and the control rules represent inevitable problems. Generally, these parameters are selected through trial and error or are the result of the designers’ experiences.

Recently, modern heuristic optimization techniques, such as simulated annealing (SA) [11], genetic algorithms (GA) [12], evolutionary programming (EP) [13], tabu search (TS) algorithms [14], neural network approaches, differential evolution (DE) algorithms [15], ant colony optimization (ACO) [16], particle swarm optimization (PSO) [17], and the bee algorithm (BA) have received much attention from researchers because of their abilities to find an almost globally optimal solution.

This paper focuses on the design of optimal PID, SM, and FSM controllers for the DVR system. Without trial and error, all control parameters of the PID, SM and FSM controllers can be automatically designed by the BA. The comparison was carried out by assigning a performance index in terms of voltage error. The effectiveness of this control strategy has been demonstrated through simulations and experimental tests carried out in different case studies.

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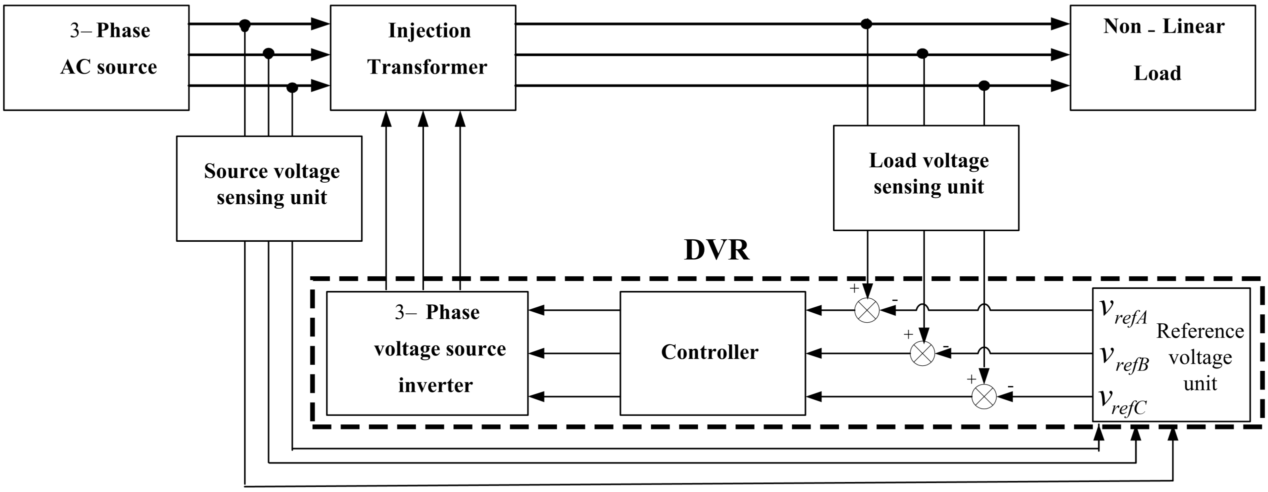



***Fig.1:*** *A block diagram of a 3-phase DVR power system.*

## 2. PROBLEM FORMULATION

The block diagram of a 3-phase DVR power system is shown in Fig. 1 [18]. The system consists of five main components: a 3-phase AC source, an injection transformer, a DVR, source and load voltage sensing units, and non-linear loads. For a 3-phase AC source, injection transformers and non-linear loads are well-known basic components. Therefore, this paper has solely focused upon the DVR information.

The DVR is an electronic power device, which has excellent dynamic capabilities. The function of the DVR is to compensate the load voltage during the effects of voltage sags and swells. In this paper, the proposed DVR consists of three components: a 3-phase voltage source inverter, a reference voltage unit (RVU), and a controller (shown in Fig. 1).

### 2.1 A 3-phase voltage source inverter

A voltage source inverter is commonly used to convert DC voltage to AC voltage with variant amplitude, frequency, and phase in relation to the specific power electronic devices and switching controls [19]. In this paper, the multiple pulse width modulation (MPWM) method was used to switch the inverter. The advantages of the MPWM are its simple operation, fast action, and its low voltage harmonic. The circuit diagram and the signal waveforms of a MPWM voltage source inverter are shown in Fig. 2.

The output voltage of a MPWM voltage source inverter is controlled by the on/off states and the pulse widths of the control signal. The control signals have 2 signals per phase. Therefore, the 3-phase system has 6 control signals with each phase alternating 120 degrees. Therefore, the root mean square (rms) output voltage of the inverter can be calculated by [20]:

$$V_{o(\mathrm{rms})} = \sqrt{\frac{2pV_{o(\mathrm{width})}}{\pi}} \tag{1}$$

in which $V_{o(\mathrm{width})}$ is output pulse width. $p = f_s/2f_o$ is the switching pulses per cycle/2. $f_o$ is the frequency of the output pulses. $f_s$ is the frequency of the switching pulses.

The phase voltage is calculated by:

$$V_{p(\mathrm{rms})} = \frac{1}{\sqrt{2}} V_{dc} \tag{2}$$

in which $V_{p(\mathrm{rms})}$ is the rms phase voltage and $V_{dc}$ is DC suply voltage.

### 2.2 Reference Voltage Unit (RVU)

The control signal ($U$) of the controller is the error signal which represents the difference between the reference voltages ($V_{ref}$) and load voltages ($V_{load}$). The function of RVU is to receive the 3-phase source voltages and to generate the reference voltages. Therefore, the 3-phase instantaneous line to line reference voltages can be calculated by Eq. 3.

$$\begin{bmatrix} v_{refA} \\ v_{refB} \\ v_{refC} \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} 0 \\ v_{adj} \\ 0 \end{bmatrix} \tag{3}$$

These reference voltages ($v_{refA}$, $v_{refB}$, $v_{refC}$) are used to compare load voltage to input signals of the controllers.

The adjust voltage ($v_{adj}$) is the voltage which needs to be adjusted. This value may be determined by Eq. 4.

$$v_{adj}(t) = \frac{V_{rated}}{V_A(k)} \times v_A(t) \tag{4}$$

in which $V_{rated}$ is the magnitude of the rated source voltage under normal condition (fix value), $\alpha = e^{j2\pi/3}$ is the 120° phase-shift operator. $v_A(t)$ represents the instantaneous voltages of phase A. $V_A(k)$ is the amplitude of instantaneous voltage of phase A which is generated by RVU.

The $v_A(t)$ may be defined by Eq. 5.

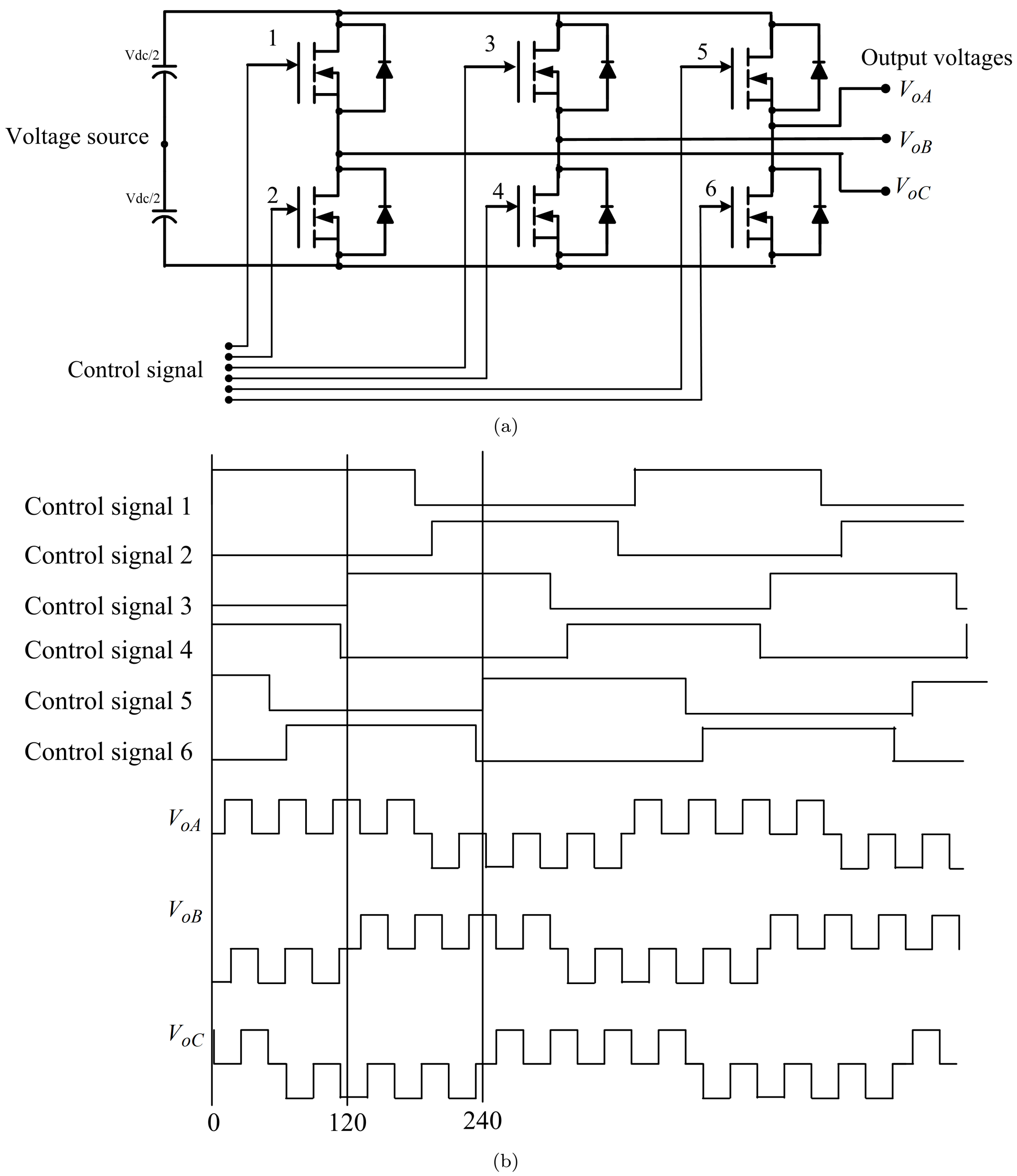



***Fig.2:*** *MPWM voltage source inverter: (a) circuit diagram and (b) signal waveforms.*

$$v_A(t) = V_A \sin(\omega t + \varphi) \tag{5}$$

In the RVU, the amplitude of instantaneous voltages of RVU, $V_A(k)$, can be calculated by sampling data during brief occurrences of two instantaneous voltages as shown in the following equation:

$$V_A(k) = \frac{\left[v_{A(k+1)}^2 + v_{A(k)}^2 - 2v_{A(k+1)}v_{A(k)}\cos(\omega T_S)\right]^{0.5}}{\sin(\omega T_S)} \tag{6}$$

in which, $v_{A(k+1)}$ and $v_{A(k)}$ is the instantaneous $v_A$ at time $t_{(k+1)}$ and $t_{(k)}$, respectively. $T_S$ represents the sampling frequency, for which the sampling time duration is equal to $t_{(k+1)} - t_{(k)}$.

### 2.3 Proposed optimal controller

This paper focused on applying BA in order to design the three optimal controllers (PID, SM and FSM). The details of these controllers are described below.

#### 2.3.1 PID Controller

The PID controller is the most popular feedback controller used in process industries. It has been successfully used for over 50 years because it is a ro-

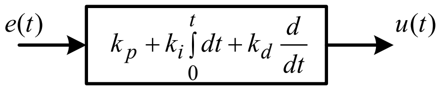



***Fig.3:*** *A block diagram of the PID controller.*

bust, easy-to-understand controller that can provide excellent control performance despite the varied dynamic characteristics of processing plants. As the name suggests, PID controllers consist of three basic modes, the proportional, the integral, and the derivative modes. A proportional controller has the effect of reducing the rise time, but never eliminates the steady state error. If the proportional gain is too high, the system can become unstable. Yet, a small gain can result in a small output response to a large input error, which means a less responsive or less sensitive controller. An integral controller has the effect of eliminating the steady-state error, but it may also worsen the transient response. High integral gain can cause overshoot and a low value, which will make the system sluggish. A derivative controller has the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response. If the derivative gain is sufficiently large enough it can cause the process to become unstable.

The conventional PID controller is a well-known technique used in the industrial control process. The design of this controller requires three main parameters: proportional gain ($k_p$), integral gain ($k_i$), and derivative gain ($k_d$). Based on experience and the behaviour of the plant, the gains of the controller are tuned through the trial and error method. The transfer function of the PID controller is shown in Fig. 3 [21].

The input signal is error $e(t)$. The control signal $u(t)$ is determined by the following equation:

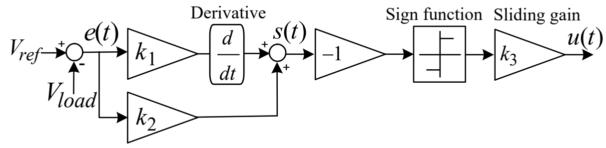
$$u(t) = \left(k_p + k_i \int_0^t dt + k_d \frac{d}{dt}\right) e(t) \tag{7}$$

In designing the optimal PID controller, the controller gain ($k_p$, $k_i$, and $k_d$) are determined by BA.

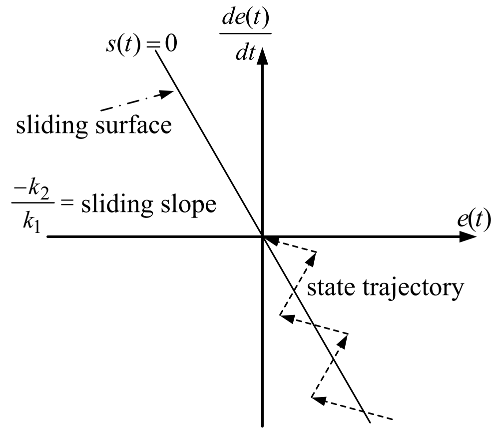
### 2.3.2 Sliding Mode Controller

The SM controller is based on the concept of varying the structure of the controller by changing the states of the system in order to obtain a desired response [7, 22]. A high-speed switching function is used to switch between different structures and the trajectory of the system is forced to move along a chosen sliding surface in the error plane. The main advantage of the SM controller is its insensitivity to variations in the system's parameters, external disturbances, and modelling errors. The structure and sliding surface of the SM controller are shown in Fig. 4.

The switching function $s(t)$ is defined by:




(a)




(b)

***Fig.4:*** *(a) Structure and (b) sliding surface of SM controller.*

$$s(t) = k_1 \frac{d}{dt} e(t) + k_2 e(t) \tag{8}$$

while $s(t) = 0$

$$\frac{d}{dt} e(t) = -\frac{k_2}{k_1} e(t) \tag{9}$$

Therefore, the sliding slope $= -\frac{k_2}{k_1}$ in which $e(t)$ is tracking error. $k_1$ and $k_2$ are the gains of the sliding slope.

The variable structure control law of the SM controller is given by the following:

$$u(t) = -k_3 \ \mathrm{sgn}(s(t)) \tag{10}$$

or

$$u(t) = \begin{cases} -k_3 & \text{if } s(t) \geq 0 \\ k_3 & \text{if } s(t) < 0 \end{cases} \tag{11}$$

in which $k_3$ is the sliding gain, and $\mathrm{sgn}(\cdot)$ is the sign function.

For the SM controller design, the gains of switching function ($k_1$ and $k_2$) and sliding gain ($k_3$) are determined by BA.

### 2.3.3 Fuzzy Sliding Mode Controller

Fuzzy logic (FL) controller is used to control the complex, imprecise, non-linear, or time-varying systems. The advantages of the FL controller are its ease of implementation because there is no need for a mathematical model of the controlled system. Furthermore, the FL controller's feature of smooth control action can be used to overcome the disadvantages

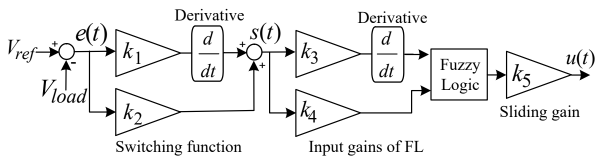



***Fig.5:*** *The structure of the FSM controller.*

of the SM controller. Therefore, the fuzzy sliding mode (FSM) controller was constructed by combining the FL with the SM. Therefore, the advantages of the FSM controller are to compensate for modeling imprecision, external disturbances, low damping, and reduced chattering [23].

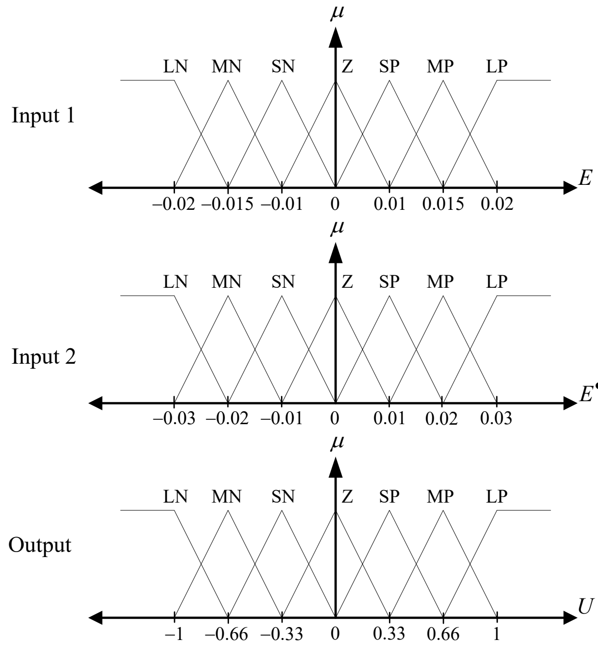
The structure of the FSM controller is shown in Fig. 5. The FSM controller consists of a switching function, input gains of FL, FL, and a sliding gain. The switching function and sliding gain of the FSM controller have the same configurations as the SM controller. The sign function has been replaced by the input gains and FL controller. The components of the FL controller are membership function (MF) and rule base (RB). This study utilized the two inputs and a single output of the FL controller. Here, the seven shapes of a MF were considered: 5 triangular memberships, 2 trapezoidal memberships, and the control rule of FSM controller. These are shown in Fig. 6. In order to design the FSM controller, the gains of switching function ($k_1$ and $k_2$), the input gains of FL ($k_3$ and $k_4$), and sliding gain ($k_5$) were determined by BA.

## 3. OPTIMAL CONTROLLER DESIGN

### 3.1 Bee Algorithm

The bee algorithm is an optimization algorithm inspired from the natural foraging behaviour of honey bees. BA was proposed by Pham, et al. [24]. The algorithm mimics the food foraging behaviour of swarms of honey bees. Honey bees use several mechanisms like waggle dance to optimally locate food sources and to search for new ones. This makes them a good candidate for developing new intelligent search algorithms. It is a very simple, robust, and population-based stochastic optimization algorithm. In BA, the colony of artificial bees contains two groups of bees which are scout and employed bees. The scout bees have the responsibility of finding new sources of food. The responsibility of the employed bees is to determine a food source within the neighbourhood of their previous food sources (stored in their memories) and to share their information with other bees within the hive.

In the BA algorithm,the following parameters are received as its inputs: the number of bees ($n$), number of sites selected out of $n$ visited sites ($m$), the number of best sites out of $m$ selected sites ($e$), the number of bees recruited for each best $e$ site ($ne$), the number of




(a)

| | | $E^{\bullet}$ | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | LN | MN | SN | Z | SP | MP | LP |
| | LN | *LP* | *LP* | *LP* | *MP* | *MP* | *SP* | *Z* |
| | MN | *LP* | *MP* | *MP* | *MP* | *SP* | *Z* | *SN* |
| | SN | *LP* | *MP* | *SP* | *SP* | *Z* | *SN* | *MN* |
| $E$ | Z | *MP* | *MP* | *SP* | *Z* | *SN* | *MN* | *MN* |
| | SP | *MP* | *SP* | *Z* | *SN* | *SN* | *MN* | *LN* |
| | MP | *SP* | *Z* | *SN* | *MN* | *MN* | *MN* | *LN* |
| | LP | *Z* | *SN* | *MN* | *MN* | *LN* | *LN* | *LN* |

(b)

***Fig.6:*** *(a) Membership function and (b) control rule of FSM controller. LN: large negative; MN: medium negative; SN: small negative; Z: zero; SP: small positive; MP: medium positive; and LP: large positive.*

bees recruited for the other ($m-e$) selected sites ($ns$), and the number of scout bees ($s$). $NC$ represents the number of iteration, while $ngh$ is the neighbourhood size. The procedures for the BA algorithm are given below:

*Step 1:* Randomly generate the initial populations of $n$ scout bees. These initial populations must be feasible candidate solutions that can satisfy the constraints ($NC = 0$).

*Step 2:* Evaluate the fitness value of the $n$ initial populations.

*Step 3:* Select the best ($m$) sites for neighbourhood search.

*Step 4:* Separate the best ($m$) sites into two groups: 1) the first group has the best ($e$) sites, and 2) the other group has the best ($m - e$) sites.

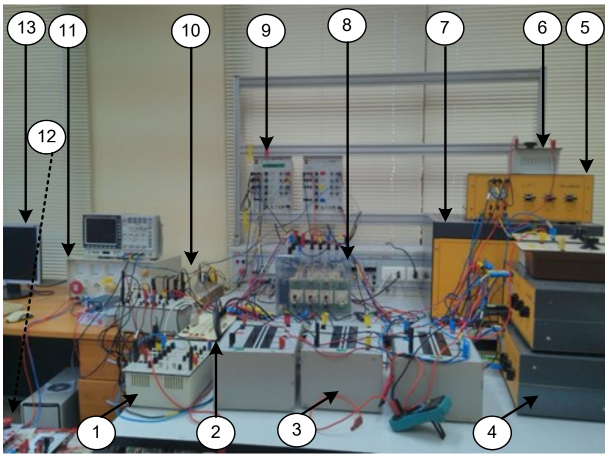



***Fig. 7:*** *Experimental setup of DVR system.*

*Step 5:* Determine the size around each best site of the neighbourhood search (patch size, $ngh$).

*Step 6:* Recruit bees for selected sites (more bees for the best ($e$) sites).

*Step 7:* Select the fittest bees from each patch.

*Step 8:* Check the stopping criterion. If satisfied, terminate the search (or else $NC = NC + 1$).

*Step 9:* Assign the remaining $(n - m)$ bees to the random search. Go to Step 2.

### 3.2 Application of BA to design the controllers

The following controllers have been individually designed for comparison studies.

1. Optimal PID controller
2. Optimal SM controller
3. Optimal FSM controller

The simulation was carried out using a MATLAB 2016-Simulink Program and the Fuzzy Logic Toolbox. The simulation was run on a laptop computer (Intel Core i5-5200u, 2.20 GHz, Ram 4 GB, Windows 8).

In this paper, the integral of time-multiplied absolute error (ITAE) of the total voltage error of each phase was selected as the performance index. Accordingly, the objective function ($J$) was set by:

$$\text{Minimize} \quad J = \int t \cdot |e| dt \qquad (12)$$

The control signal ($U$) of the controller was the error signal which was the difference between the reference voltages ($V_{ref}$) and load voltages ($V_{load}$). This study used a 3-phase sequence analyzer to determine the magnitude of error voltage from the error signal.

The procedures of the BA for the design of the PID, SM, and FSM controllers are shown below:

*Step 1:* Randomly generate the initial populations (parameters of PID or SM or FSM) of the $n$ scout bees. These initial populations must be feasible candidate solutions that satisfy the constraints (Set as $NC = 0$).

*Step 2:* Simulate the model and evaluate the fitness value (performance index) of the $n$ initial populations.

*Step 3:* Select the best $m$ sites for neighbourhood search.

*Step 4:* Separate the best $m$ sites into two groups: 1) the first group has the best $e$ sites and 2) the other group has the best $m - e$ sites.

*Step 5:* Determine the size around each best site of neighbourhood search (patch size, $ngh$).

*Step 6:* Recruit bees for selected sites (more bees for the best $e$ sites).

*Step 7:* Select the fittest bees from each patch.

*Step 8:* Check the stopping criterion (the voltage error less than setting error). If satisfied, terminate the search (or else $NC = NC + 1$).

*Step 9:* Assign the $n-m$ remaining bees to random search. Go to Step 2.

## 4. EXPERIMENTAL SETUP AND SIMULATION MODEL

### 4.1 Experimental Setup

In order to prove the concept, the experiment setup of the DVR system was as shown in Fig. 7. The components of the experiment were as follows:

(1) dSPACE: a high performance digital controller board (Model: DS1104)

(2) ATTL to CMOS voltage level converter board

(3) An injecting transformer: 1 kVA, Ratio 1:1

(4) C harmonic filter: 12 $\mu$F, 900 VAr

(5) L harmonic filter: 200 mH, 900 VAr

(6) A three-phase L load: 550 mH, 900 VAr

(7) A three-phase R load: 250 $\Omega$, 1.2 kW

(8) A three-phase inverter module

(9) A measurement board consisting of voltage and current transducers

(10) An interface panel board

(11) A variable three-phase voltage source

(12) A sag/swell control switch

(13) Control Desk software

### 4.2 Simulation Model

The 3-phase DVR power system was implemented using the Simulink model as shown in Fig. 8. The system was composed of a three-phase AC voltage source, which had been connected to a three-phase transmission line and loads. A three-phase injecting transformer and a three-phase voltage source inverter were connected in between the three-phase voltage source and loads.

## 5. CASE STUDIES AND RESULTS

### 5.1 Experiment study and result

Balance Voltage Sags: The experimental results of a load voltage in the case of voltage sag are shown in Fig. 9. When the source voltage dropped to 130

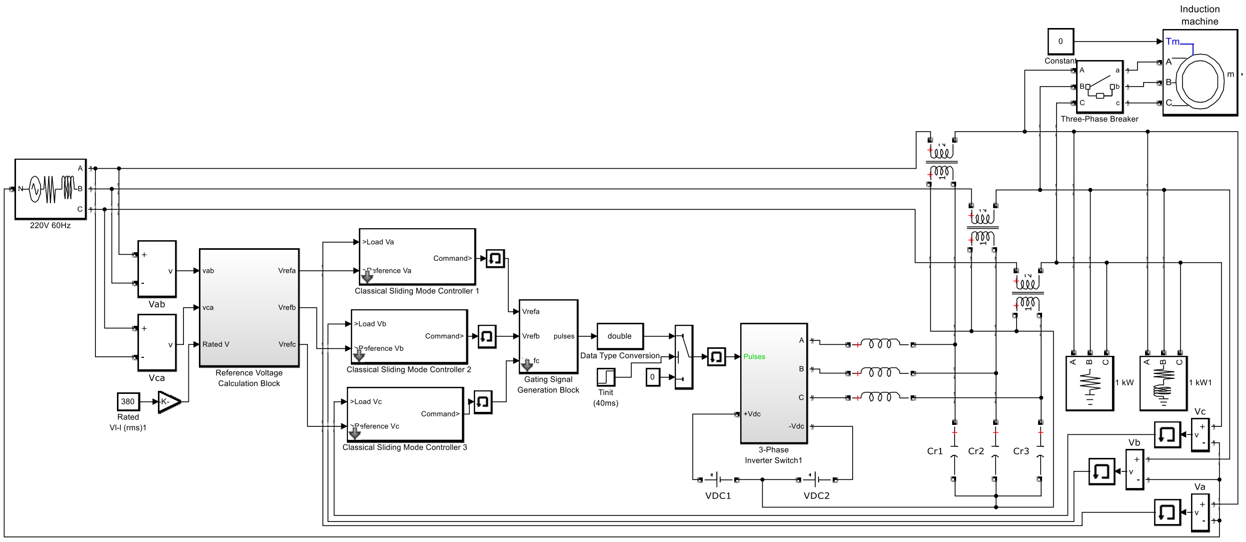



***Fig. 8:*** *The Simulink model of the DVR system.*

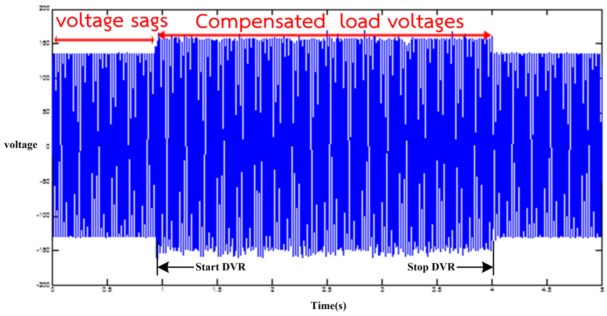



***Fig. 9:*** *Waveform of phase voltage in the case of voltage sag.*

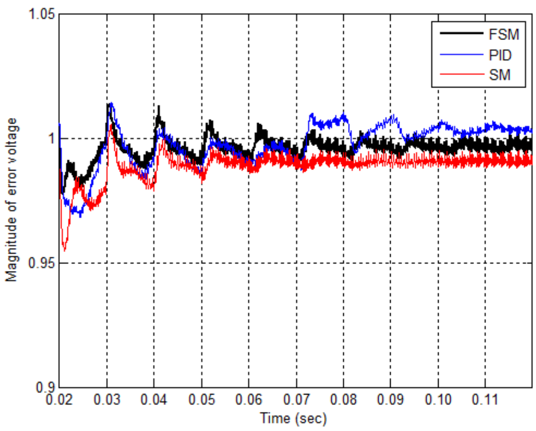



***Fig. 10:*** *The magnitude deviations of error voltage after the voltage sags.*

$V_{peak}$, the DVR was activated at 0.95 s and the load voltage was compensated to a set voltage of 150 $V_{peak}$. When the DVR was non-activated at 4 s, the load voltage would drop again.

## 5.2 Simulation studies and results

According to the data obtained from many experiments, the following are the parameters of the BA approach:

- Maximum iterations ($N_{MAX} = 300$)
- Number of scout bees ($n_s = 10$)
- Number of best selected sites out of $n_s$ visit sites ($m_s = 5$)
- Number of best selected sites out of $m_s$ selected ($e_s = 2$) sites
- Number of employed bees recruited for the $e_s$ best sites ($n_{ep} = 10$)
- Number of employed bees recruited for other ($m_s - e_s$) selected sites ($n_{sp} = 5$)
- Neighborhood size ($n_{size} = 10\%$)

*Case 1: Balance Voltage Sags* Let us assume that the voltage source occurs at all phase voltages sags from 1 p.u. to 0.3 p.u. during 20–80 ms of time. In order to maintain the load voltage at 1 p.u. at all times, the PID, SM, and FSM controllers of the DVR would inject a compensating voltage to the system. The results are the tuned parameters of three controllers, which are shown in Tab. 1. In Fig. 10, the magnitude deviations of error voltage after the voltage sags are shown. The waveform of the load voltages in the case of voltage sags are shown in Fig. 11.

*Case 2: Balance Voltage Swell* The simulation result in the case of a balance voltage swell is shown in Fig. 12. It can be assumed that as the voltage source occurs, all voltages swell from 1 p.u. to 1.8 p.u. during 20–80 ms of time. The FSM controller of DVR would inject compensating voltage into the system in order that a load voltage of 1 p.u. can be maintained at all times.

***Table 1:*** *The tuned parameters of the three controllers*

| Parameter | PID | SM | FSM |
|---|---|---|---|
| $k_p$ | 1890.12 | – | – |
| $k_i$ | 54.60 | – | – |
| $k_d$ | 8.80 | – | – |
| $k_1$ | – | 591.86 | 1.00 |
| $k_2$ | – | 20.81 | 1104.90 |
| $k_3$ | – | 11.10 | 1.02 |
| $k_4$ | – | – | 1208.76 |
| $k_5$ | – | – | 320 |
| ITAE | 0.0227 | 0.0425 | 0.0179 |

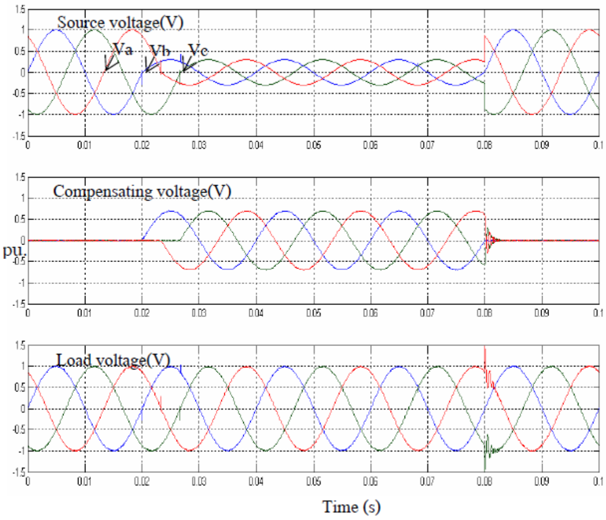



***Fig.11:*** *Waveforms in the cases of voltage sags.*

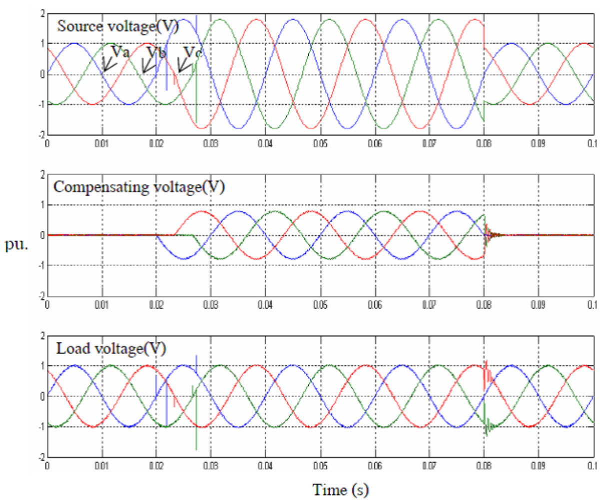



***Fig.12:*** *Waveform in the case of voltages swell.*

## 6. CONCLUSION

This study presents the use of a bee algorithm as a powerful artificial intelligence-based optimization technique, which can be used to optimize the parameters of the PID, SM and the FSM controllers and to conduct a comprehensive analysis of its tuning performance. In order to reveal the tuning performance of the BA, it was applied to the DVR system to compensate for the sags and swells of the source voltage. Then transient response method was applied to obtain the analytical results and to determine the tuning superiority of the BA. Consequently, from this study, it was revealed that the BA could be successfully applied to the DVR system and that its tuning capability was proved.

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