PID-Controller Tuning of Brushless DC Motor by Using ACO (Ant Colony Optimization) Technique

By

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CERTIFICATION OF APPROVAL

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Approved:

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TRONOH, PERAK

September 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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SIAW KAH JING

ABSTRACT

ACO stands for Ant Colony Optimization which it automatically finds the best solution or the best PID controller parameters for the targeted control system. ACO algorithm is used as the technique for the PID controller parameters optimization. It functions in finding and obtaining optimum values of gain, integral time and derivative time for the PID controller. At the testing stage, the ACO algorithm is developed by using MATLAB. The ACO algorithm will calculate the ISE (Integral Square Error) for each set of PID parameters. and then comparison is done on the different values of ISE from different sets of PID parameters to choose the best PID parameters set with the lowest ISE. As a result, a performance curve of ACO that is as closed as to the set-point with high performances (lower overshoot value, shorter system dead time and settling time and lower ISE if compared to the conventional PID tuning methods) is obtained.

ACKNOWLEDGEMENT

I would like to thank my supervisor, AP. Dr. Irraivan Elamvazuthi who had been giving me proper guidance and valuable advice in completing this research. I am very sure that it would not be possible without his helping hand. Other than that, this dissertation would not be possible without the constant support from my parents, course mates and friends as well.

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1.0 Introduction

1.1 Background Study of PID Controller

PID controller is being applied in industrial control system widely. Since it is a generic control loop feedback, it calculates errors which are the differences between desired set-point value and the measured process variable and thus it does corrections on the gain of each PID parameters to minimize the occurred errors. The proportional gain value determines the current error reaction; the integral gain value determines the sum of recent errors reaction while the derivative gain value is based on the rate at which the error has been changing the weighted sum of these three actions is used to adjust the process via the final control element. [1]

PID parameters (proportional, integral and derivative gains) are summed for calculating PID controller output. The PID algorithm final form controller output is:

$$\mathrm{u}(t) = \mathrm{MV}(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{d}{dt} e(t)$$ -----------(Eqn. 1.1.1)

Where:

Kp= Proportional gain

Ki= Integral gain

Kd= Derivative gain

e= Error= SP-PV

t= Time

Proportional Term

An output value is produced by the proportional term that is proportional to the current error value. By multiplying a constant Kp (proportional gain) that can be adjusted by the proportional response. The equation of the proportional term is:

$$P_{\text{out}} = K_p\, e(t)$$ --(Eqn. 1.1.2)

The higher the proportional gain, the larger is the output change for a given error change. A small output response is the result of a small gain to a large input error. Thus, when responding to disturbances of the system, the control action maybe too small and this has created a less responsive and less sensitive PID controller. In other way round, the system would be unstable if the proportional gain is too high.

Integral Term

Integral term contributes as it proportions to the error duration and also the magnitude of error. It is the sum of the instantaneous error over time that gives the accumulated offset values which are previously corrected. The equation of the integral term is:

$$I_{\text{out}} = K_i \int_0^t e(\tau)\, d\tau$$ --(Eqn. 1.1.3)

The integral term speeds up the process movement towards setpoint and together with a pure proportional controller, the residual steady-state error can be eliminated.

Derivative Term

By determining the error slope over time and multiplying the derivative gain, Kd with this rate of change, the process error derivative can be calculated. The equation of the derivative gain, Kd is:

$$D_{\text{out}} = K_d \frac{d}{dt} e(t)$$ --(Eqn. 1.1.4)

Figure 1 shows the example of Set-point and PV. The controller output rate of change is slowed down by the derivative term. The overshoot magnitude that is produced by the integral component can be reduced by using derivative control. Thus, the stability of the combined controller-process can be improved. However, the transient response of the controller could be slowed down.

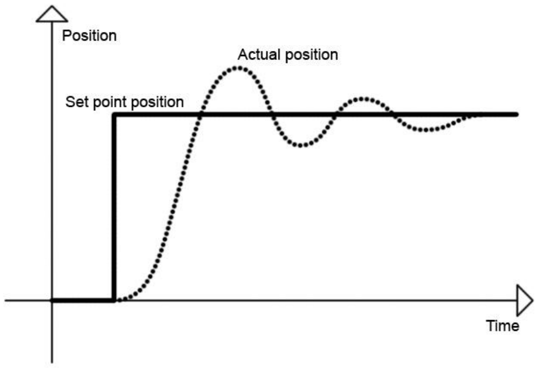

Figure 1: Example of Set-point and PV[27]

1.2 Background Study of ACO (Ant Colony Optimization)

In year 1991, Marco Dorigo has invented ACO in collaboration with Colorni and Maniezzo. Inspiration is drawn by ACO from the real ants behavior to provide an optimization method. ACO is normally dealing with combinatorial optimization problems such as TSP (Travelling Salesman Problem), facility placement, scheduling and so on but also extended for solving other problems.

Figure 2 shows the ACO simulation. The ants leave a pheromone trail when the ants have passed through a certain routes. The following ants are more likely or tend to take the route with higher concentration of deposited pheromone when choosing a route. They will follow the route with the most concentrated pheromone which gives them the shortest path to the destination when the first ants are returning home. The rules are probabilistic. If locally, a more minimal path is found, changes are allowed by the evaporation of the pheromones.

Stigmergy is an indirect communication which is exploited by a colony of insects for coordinating their activities. The constructions regulation and the tasks coordination does depend on the constructions themselves but not directly on the workers. The workers are guided by it but not direct their works. Stigmergy is important because it allows simpler agents, decreases direct communication and allows appropriate response when the agents are changed by the environment.

With ACO, we can have a colony of artificial ants which lay a trail in the search space of some problems. The problems might include the seeking or searching of a shorter path and also making the right decision from a certain alternatives. Furthermore, ACO is also using artificial stigmergy as its working principle.

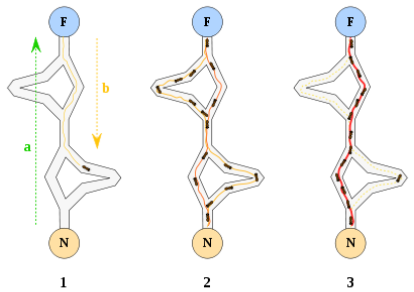

Figure 2: ACO Simulation[28]

1.3 Problem Statement

There are simple but effective solutions are provided to most of the control engineering applications nowadays by the PID control schemes. Thus, it is widely being used in various industries in order to rule or to regulate the behaviors of time domain of many different types of dynamic plants.

Figure 3 shows the characteristics of conventional PID tuning. In brushless DC motor speed controlling application, there are different ways of PID controller tuning including hand tuning techniques, namely Ziegler-Nichols tuning method and also Cohen-coon tuning method in plants. These conventional techniques have their own limitation such as time consuming (less efficient) in obtaining optimum gains for the PID control schemes. This is because conventional PID controller tuning methods such as Ziegler-Nicholes and Cohen-coon requires offline tuning. Thus, pro-long process shut down couldn't be avoided for every offline tuning. The conventional PID controller tuning methods are costly because specialists or professional tuners are required for the tuning. The conventional PID controller tuning methods are high in labor dependencies and thus, tuning is not possible if there is shortage of labor. Manual tunings are not free from human errors. Thus, they give inconsistent and poorer performances qualities. Unstable system controller is unsafe and unreliable.

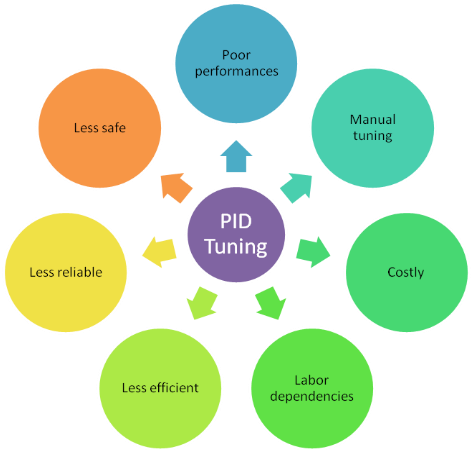

Figure 3: Characteristics of Conventional PID Tuning

1.4 Objective

ACO intelligent technique allows automatically tuning on real process model. If the original model is too complex, model reduction is necessary for conservative methods. For example, without ACO, the original model might be needed to be reduced to first order plus dead time model (FOPDT) in order to be tuned by hand tuning methods.

In brushless DC motor speed controlling application, ACO enables the control system becomes more customizable where this method optimizes some design criteria such as phase and gain margins to characterize the closed-loop system properties more appropriately.

For ACO, there is no assumption or approximation as that is needed by Ziegler-Nicholes tuning and also Cohen-coon tuning.

Ant Colony Optimization (ACO) is feasible to be used in finding solutions for different optimization problems of control systems and in this application, ACO seeks and searches for the desired optimal gain for the BLDC motor control system that we can the optimal motor speed that we want. A colony of artificial ants is cooperating in finding good solutions (optimum gains for PID controller). By applying natural behaviour of ant colonies, ACO is adaptive and robust; also, it can be applied to various optimization problems of control system.

Figure 4 shows the features of ACO in PID tuning. For applications in oil and gas industry, since ACO is a self-tuning technique (automatic), it has overcame the weaknesses of manual tuning technique as ACO ensures low execution or maintaining cost with low labor dependency, high efficiency, high reliability, more safe and also outstanding good performances.

Figure 4: Features of ACO in PID Tuning

2.0 Literature Review

2.1 Types of Motors

Introduction

Electric motors are the devices which converts the energy from the form of electrical energy into mechanical energy. Through interaction of current-carrying conductors and magnetic field, motors operate to generate force. Some applications of electric motors are motor valve, pumps, blowers, industrial fans and many others.

Operating principle

Most of the electric motors are functioning based on magnetism. Magnetic fields are formed in these motors in both the rotor and the stator. As a result, a force is produced between the interaction of these two fields and thus a torque on the motor shaft. With the motors rotation, at least one of these fields is or are to be varied and this can be done by switching the poles on and off at the right time or changing the strength of the pole.

Categorization

There are two main types of motors namely, DC motors and AC motors. For synchronism between a moving current sheet and a moving magnetic field for average torque action among all the rotating or linear electric motors, there is a clear distinction between an asynchronous motors and synchronous motors. Asynchronous motors need slip where relative movement between the magnetic field and a winding set are required for inducing current in the rotor by mutual inductance. However for synchronous motors, slip or induction is not required for current production of magnetic field.

DC motors

DC motors are the motors to operate on DC electric power. There are two the most common types of DC motors namely, brushed and brushless types. The brushed DC motors use internal commutation to reverse the current in the windings in synchronism with rotation whereas the brushless DC motors use external commutation to reverse the current in the windings in synchronism with rotation.

2.2 BLDC Motor

Introduction

BLDC motors are one of the most popular types of motors in the manufacturing, merchandising and oil and gas industries. BLDC motors are electronically commutated instead of using brushes. If compared to brushed DC motors, BLDC motors are better in speed versus torque characteristics, higher in dynamic response, higher in efficiency, longer in operating life, more noiseless in operation, higher in speed ranges, higher in the ratio of torque delivered to the size of the motors.

Construction and operating principle

BLDC motors are synchronous motors which means the magnetic field generated by the rotor and the magnetic field generated by the stator rotate at the same frequency. BLDC motors do not require 'slip' as the induction motors. There are single-phase, 2-phase and 3-phase configurations for BLDC motors. The windings number for the stator is the same in corresponding to its type. The most commonly used BLDC motors are 3-phase motors.

Stator

Figure 5 shows stator of a BLDC motor. There are stacked steel laminations at the stator of a BLDC motor with windings placed in the slots that are axially cut along the inner periphery. The stator resembles that of an induction motor traditionally but in a different manner the windings are distributed. The connection of three stator windings in most BLDC motors is done in star fashion. A winding is formed with numerous coils interconnected, each of these windings are constructed. To make a winding, one or more interconnected coils are placed in the slots. To form an even numbers of poles, each of these windings is distributed over the stator periphery. Trapezoidal motors and sinusoidal motors are among the two types of stator windings. The difference is the basis of the coils interconnection in the stator windings to give the different types of back electromotive force (EMF).

Back EMF is the electromotive force or voltage that pushes against the current which induces it. Back EMF is depending on angular velocity of the rotor, magnetic field generated by the rotor magnets and also the number of turns in the stator windings. As indication from their names, back EMF is given back in trapezoidal fashion by the trapezoidal motors and sinusoidal fashion by the sinusoidal motors.

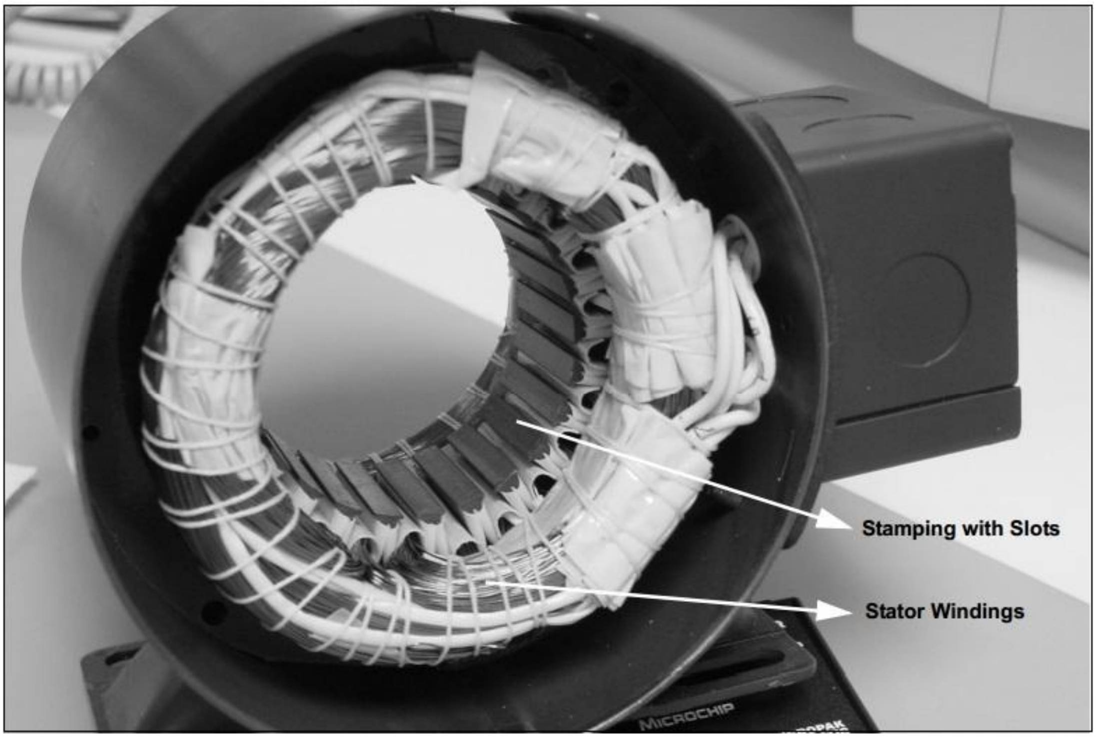

Figure 5: Stator of A BLDC Motor[13]

Rotor

Figure 6 shows rotor magnet cross sections. The rotor consists of permanent magnet. It can be varied from two to eight pairs with alternate South (S) poles and North (N) poles. To make the rotor, proper magnetic material is chosen based on the required magnetic field density in the rotor. Traditionally, ferrite magnet is used to make permanent magnets. The ferrite magnets are less expensive but they are low in flux density for a given volume. Different from ferrite magnets, the alloy material is high in magnetic density per volume an the rotor is enabled for further compression for the same torque. Moreover, the alloy magnets give higher torque and improve the size-to-weight ratio if compared to the ferrite magnets.

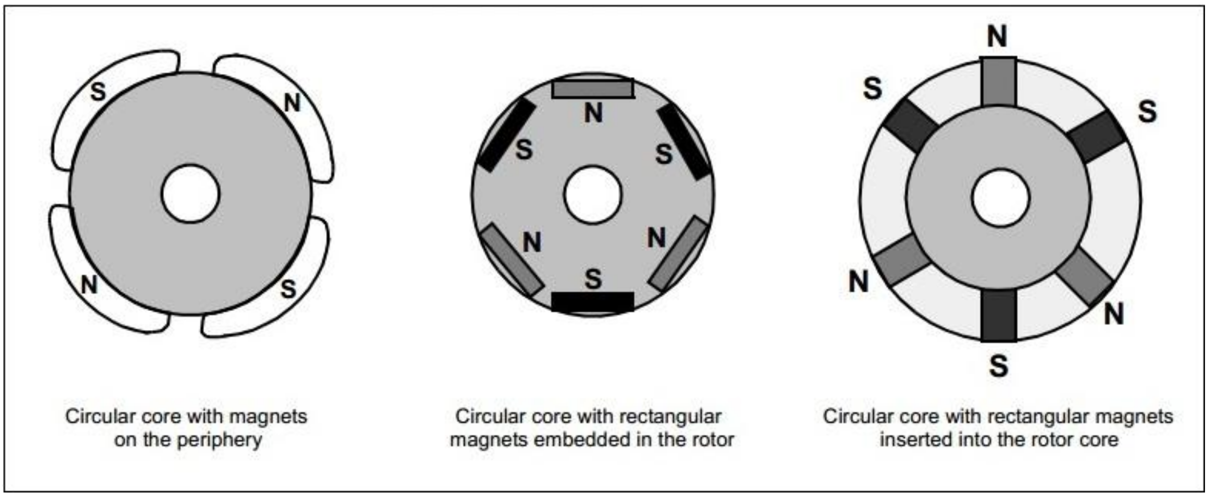

Figure 6: Rotor Magnet Cross Sections[13]

Hall sensor

The commutation of a BLDC motor is controlled electronically unlike a brushed DC motor. The stator windings should be energized in a sequence in order to rotate the BLDC motor. To understand which winding will be energized following the energizing sequence, the position of the rotor is important to be known. Consequently, by using Hall Effect sensors which are embedded into the stator, rotor position is sensed. There are three Hall sensors embedded into the stator on the non-driving end of the motor in most BLDC motors. The rotor magnetic poles give a high or low signal whenever they pass near the Hall sensors. The exact sequence of commutation can be determined based on the combination of these three Hall sensor signals.

Figure 7 shows a transverse section of a BLDC motor with a rotor that has alternate S and N permanent magnets. Into the stationary part of the motor the Hall sensors are embedded.

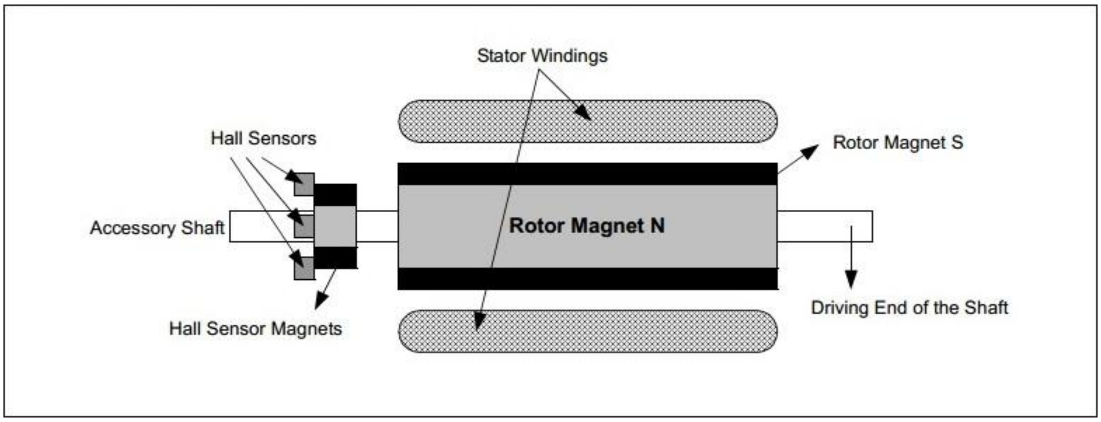

Figure 7: BLDC Motor Transverse Section[13]

Closed-loop control

Speed controlling is possible in a closed loop by measuring the motor actual speed. Thus, the error which is the difference in the set speed and the actual speed of the motor is calculated. To do this, PID controller can be used for amplifying the speed error and do adjustments to the PWM duty cycle dynamically.

For measuring the speed feedback, the Hall sensors can be utilized. To make counting between two Hall transitions, a timer can be used. The actual speed of the motor can be measured with this counting technique. Furthermore, an optical encoder can be fitted onto the motor for high-resolution speed measurements with two signals with 90 degrees phase difference will be obtained. Both speed and direction of rotation can be determined by these signals.

Besides that, most of the encoders give a third index signal, which is one pulse per revolution and this can be used to position applications. Optical encoders are available with different choices of PPR (Pulse Per Revolution) which ranges from few hundreds to few thousands.

2.3 Discussion

ACO is used as intelligent tuning technique for BLDC PID controller because ACO guarantees superior performances and has wide ranging of applications. Moreover, it is stable and robust in PID controller parameters tuning.

3.0 Methodology

3.1 Flow Chart

Figure 8 shows the flowchart of ACO application in BLDC motor.

Step 1 Initialization of number of ants, pheromone, and probability selected path.

By using uniform distribution, a random potential solutions or feasible gains are initialized for the PID controller parameters.

Step 2 The A-th ant is placed on the node and the associated heuristic value is then computed in order to reduce the offset error.

Step 3 The equation of pheromone updation is being applied to forget and eliminate the bad choices in order to avoid unlimited increase of pheromone trails.

Step 4 The solutions that are acquired are evaluated according to the behavior or characteristics of the graph obtained.

Step 5 The optimum values of the optimum gain of the PID parameters are displayed.

Step 6 The pheromone condition is updated continuously based on the optimum solutions that are calculated at step 5. Iteration is done from step 2 until the maximum of iterations is obtained.

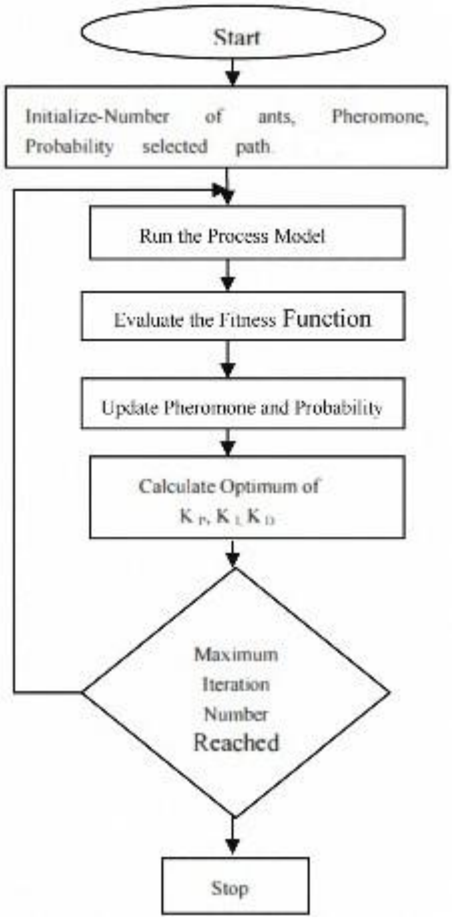

Figure 8: Flowchart of ACO Implementation[14]

3.2 ACO Related Equations

The pheromone matrix of ACO:

$\tau = \{ \tau_{ij} \}$--(Eqn. 3.2.1)

for the construction of potential good solutions.

The initial values are set to:

$\tau_{ij} = \tau_0 \forall (i, j)$--(Eqn. 3.2.2)

in condition $\tau_0 > 0$.

The probability of choosing a node j at node I is:

$p_{ij}^{A}(t) = \dfrac{[\tau_{ij}(t)]^{\alpha} [\eta_{ij}]^{\beta}}{\sum_{i,j \in T^{A}} \tau_{ij}(t)]^{\alpha} [\eta_{ij}]^{\beta}}$--(Eqn. 3.2.3)

if i, j $\in T^{A}$.

Where:

$\eta_{ij} = \dfrac{1}{k_j}, j = [p, i, d]$--(Eqn. 3.2.4)

representing heuristic functions.

Noted that α and β are constants that determine the relative influence of the pheromone values and the heuristic values on the decision of the ant while T^{A} is the path effectuated by the ant A at a given time.

The quantity of pheromone on each path is:

$$\Delta \tau_{ij}{}^{A} = \begin{cases} \dfrac{L^{\min}}{L^{A}} & if \quad i, j \in T^{A} - (6) \\ 0 & \text{else} \end{cases}$$ --(Eqn. 3.2.5)

where L^A is the value of the objective function found by the ant A while L^{min} is the best solution carried out by the set of the ants until the current iteration.

Pheromone updation is:

$$\sum_{k} \Delta \tau^{k} = \Delta \tau^{k=1} = \frac{\zeta f_{best}}{f_{worst}}$$ ---(Eqn. 3.2.6)

The pheromone evaporation is important for avoiding unlimited increase of pheromone trails:

$$\tau_{ij}(t) = p \tau_{ij}(t-1) + \sum_{A=1}^{NA} \Delta \tau_{ij}^{A}(t)$$ --(Eqn. 3.2.7)

where NA is the number of ants while P is the evaporation rate.

3.3 Block Diagram

Figure 9 shows the block diagram of implementation of ACO in BLDC controller. The BLDC motor system is ran with ACO and the fitness functions of the PID controller are calculated. From the fitness functions, the performance of BLDC motor PID control system is evaluated. ISE (Integrated Summation Error) is one of the fitness functions. The ACO algorithm will keep comparing the ISE values that are obtained from different sets PID gains until the system gets the smallest ISE value and thus the most optimum set of PID gains can be found.

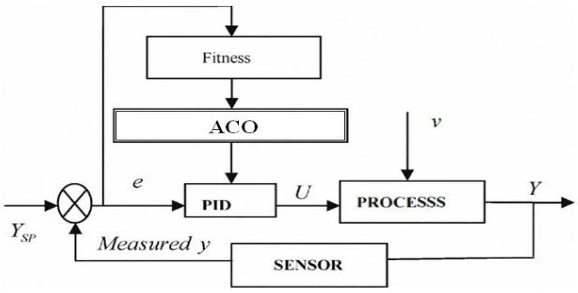

Figure 9: Block Diagram[14]

3.4 Interpretations on ACO Technique

Table 1: Interpretations on ACO

<table>
<tr><td>Sequence</td><td>Natural Behaviours of Ant Colonies</td><td>Applications In PID Control Schemes</td></tr>
<tr><td>1</td><td>When seeking for food outside, the colony of ants leave a pheromone trail.</td><td>The system is randomly seeking for PID gains in order to get the optimum gains for the system controller.</td></tr>
<tr><td>2</td><td>The rest of the ants are more likely to follow a route which has more pheromone deposited.</td><td rowspan="2">The system controller will attempt to find the optimum PID gains in the shortest time (dead-time, rise-time).</td></tr>
<tr><td>3</td><td>When the first ants are returning home, they will tend to find more pheromone on the shortest path.</td></tr>
<tr><td>4</td><td>Pheromones evaporate for allowing changes if a locally minimal route is found.</td><td>This is important to the system to allow the forgetfulness of the bad choices of the gains.</td></tr>
</table>

3.5 Tool(s)

This series of project activities are executed by using MATLAB. A smooth graph with small dead-time, short rise-time, small overshoot and zero offset error is expected to be obtained at the end of the execution.

3.6 MATLAB Simulation & Discussions

For Brushless DC Motor application, the presence of error is being related to ISE (Integral Square Error). MATLAB simulation as shown in Figure 10 will be developed to apply the ACO algorithm on the Brushless DC Motor system with known transfer function. Comparisons are made between the ACO method, Ziegler-Nichols method and also conventional PID method. The transfer function is obtained from the derivation of the BLDC Motor parameters.

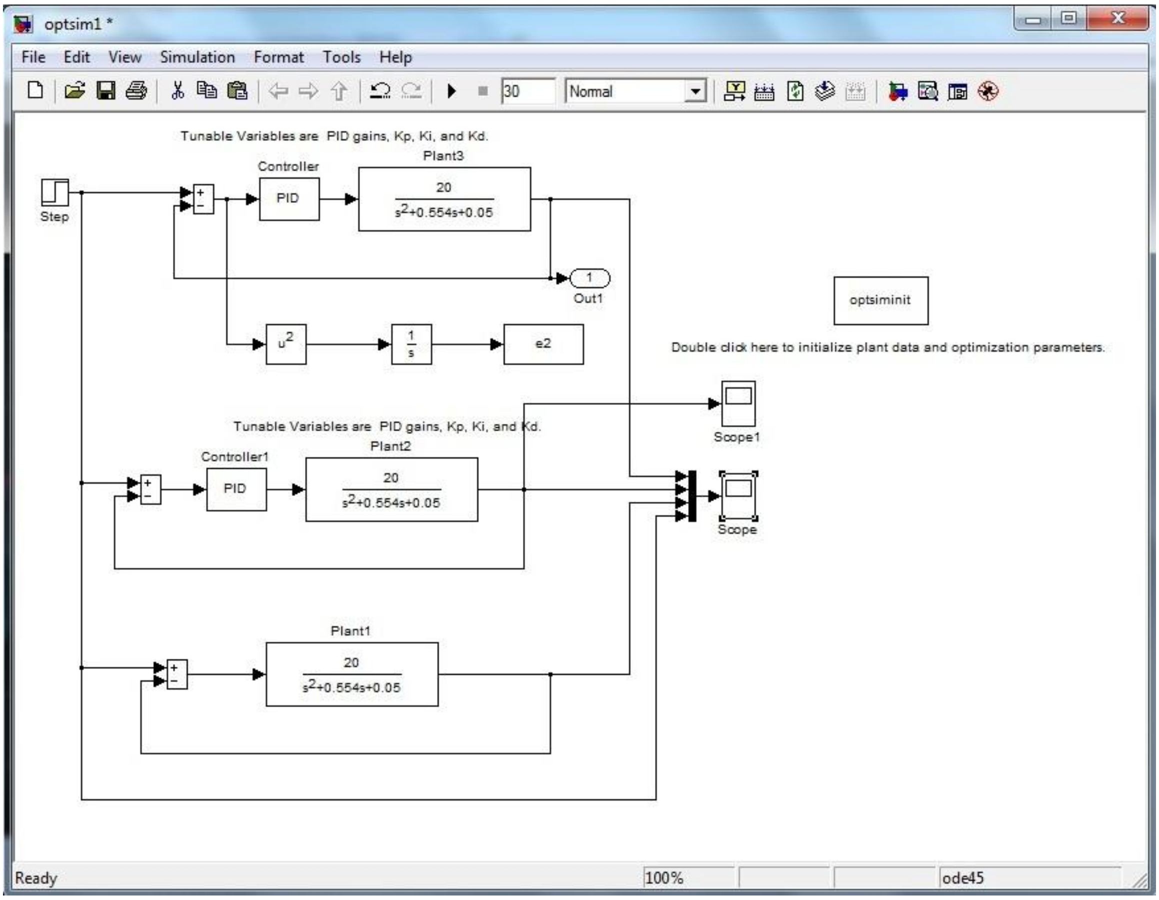

Figure 10: MATLAB Simulation

The first row is the construction of the BLDC Motor PID control system with the improvement by ACO algorithm. The second row is the construction of the BLDC Motor PID control system with Ziegler-Nichols as the tuning technique. The third row is the construction of the BLDC Motor PID control system with conventional PID method. The performance of each are being analyzed and evaluated at ‘Scope’. Thus, the comparison is being done on the performances of each tuning method.

3.7 Results & Discussions

Figure 11 consists of the curves of ACO, Ziegler-Nichols and PID so that the performances of each tuning technique on the BLDC Motor application can thus be analyzed and compared. Set-point is functioning as a reference curve.

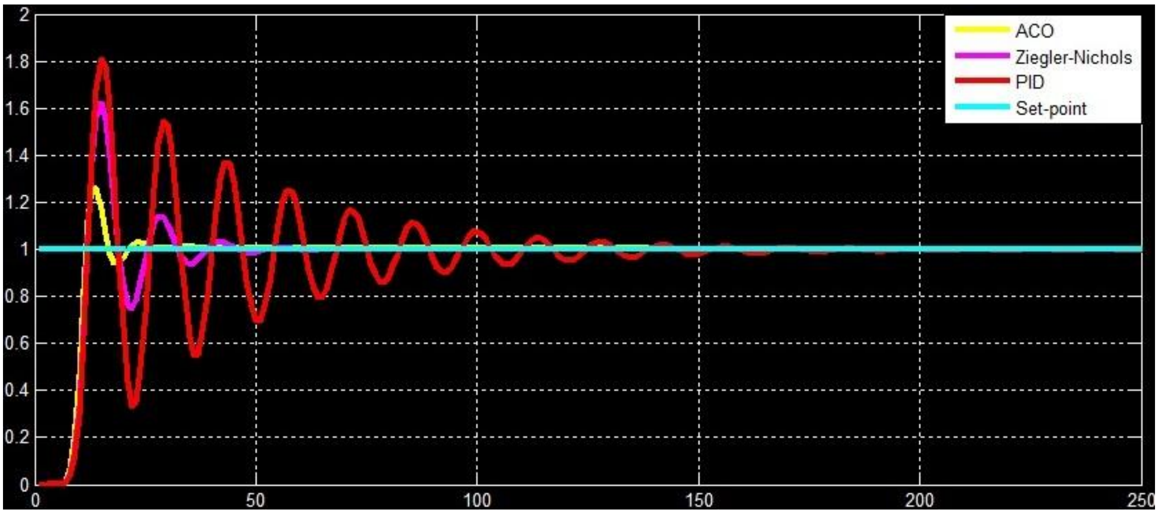

Figure 11: The Performance Curves of ACO, Ziegler-Nichols, PID and Set-point

As from the graph, ACO algorithm gives the best tuning performance on BLDC Motor application as the curve is as identical as to the set-point.

Ziegler-Nichols tuning technique gives a better tuning effect than that of the conventional PID tuning technique.

As we can see from the graph, the conventional PID tuning methods gives the poorest performance as the curve seems to be oscillating before reaching the steady-state.

Table 2: PID Parameters Gains of ACO, Ziegler-Nichols and PID

Tuning Technique	ACO	Ziegler-Nichols
P	1.9688	1.2
I	0.0504	1.71
D	0.63	0.14625

Table 3: The Performances of ACO, Ziegler-Nichols and PID

Tuning Technique	ACO	Ziegler-Nichols
ISE	5.1743115195e-21	8.6969610331e-15
Overshoot Value	0.08 (8%)	0.246 (24.6%)
Settling Time	2.5s	5.0s

From the tables, we can see that ACO tuning technique gives the best performance in the BLDC Motor PID control system as it gives the lowest value in ISE, overshoot value and also the settling time of the system. The lower the ISE value is, the closer the curve to the set-point and thus the nearer is to the desired output value. As for the overshoot value of a system, the lower the overshoot value is, the more stable the system is. Whereas, the shorter the settling time is, the faster the system reaches the steady-state. Zigler-Nichols gives a better performance than that of the conventional PID tuning technique.

4.0 Conclusion and Recommendations

4.1 Conclusion

ACO is a flexible and adaptive technique that it can be applied in most PID control system applications such as pressure controlling, temperature controlling, flow controlling, level controlling, etc. In this paper, ACO technique is mainly focused on brushless DC motor PID speeds controller system. ACO algorithm indeed gives better results or performances in term of overshoot evaluation, offset error, rise-time, settling time including other fitness functions.

4.2 Recommendations

ACO is fine to be combined with other intelligent techniques to function as hybrid tuning technique that has the good features of both combined intelligent tuning techniques which can compensate the downside of ACO. For example, ACO can be combined with GA or PSO which will give fantastic performances with almost no overshoot, almost no offset error, super short rise-time and also settling-time.

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[29] http://en.wikipedia.org/wiki/Electric_motor

[30] http://en.wikipedia.org/wiki/Brushless_DC_electric_motor

[31] http://en.wikipedia.org/wiki/Counter-electromotive_force

Appendices

Appendix 1

Gantt Chart

	Activities	Week																												
		FYP1														FYP2														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Project Selection																													
2	Preliminary Research Work																													
3	Extended Proposal																													
4	Development of Methodology																													
5	Proposal Defense																													
6	Interim Draft Report																													
7	Interim Report																													
8	Work continue from FYP1																													
9	Progress Report																													
10	Final Research																													
11	Pre-SEDEX																													
12	Draft Report																													
13	Final Report																													
14	VIVA																													

Key Milestone

Appendix 2

Motor Parameters

Electrical Parameter	Typical Symbol	Unit	Definition
Reference Voltage	V	Volts	This is the rated terminal voltage.
Rated Current	Ir	Amps	Current drawn by the motor when it delivers the rated torque.
Peak Current (stall)	Ipk	Amps	This is the maximum current allowed to be drawn by the motor.
No Load Current	I_{NL}	Amps	Current drawn by the motor when there is no load on the motor shaft.
Back EMF Constant	K_E	V/RPM or V/rad/s	Using this parameter, back EMF can be estimated for a given speed.
Resistance	R	Ohms	Resistance of each stator winding.
Inductance	L	mH	Winding inductance. This, along with resistance, can be used to determine the total impedance of the winding to calculate the electrical time constant of the motor.
Motor Constant	K_M	Oz-in/√W or NM//√W	This gives the ratio of torque to the power.
Electrical Time Constant	τE	ms	Calculated based on the R and L of the windings.

Mechanical Parameter	Typical Symbol	Unit	Definition
Speed	N	RPM or rad/s	Rated speed of the motor.
Continuous Torque	T_C	Oz-in or N-M	This is the torque available on the shaft for the given speed range.
Peak Torque or Stall Torque	Tpk	Oz-in or N-M	This is the maximum torque that motor can deliver for a short duration of time. This torque may not be available for all the speed ranges.
Torque Constant	Kt	Oz-in/A or N-M/A	This is the torque produced for every ampere of current drawn by the motor. Since the torque varies linear with current, this parameter can be used to interpolate the torque delivered for a given current and vice versa.
Friction Torque	T_F	Oz-in or N-M	This is the torque loss due to friction which includes mainly the bearing friction.
Rotor Inertia	J_M	Oz-in-s^2/N-M-s^2	Rotor moment of inertia. This is useful to determine the acceleration and deceleration rates, the dynamic response of the system and to calculate the mechanical time constant of the rotor.
Viscous Damping	D	Oz-in/RPM or N-M-s	
Damping Constant	K_D	Oz-in/RPM or N-M-s	
Temperature	T	°F or °C	Operating ambient temperature.
Maximum Winding Temperature	θmax	°F or °C	Maximum allowed winding temperature. If the winding temperature exceeds this limit, winding leakage current may increase or there are chances of winding breakdown.
Thermal Impedance	R_{TH}	°F/W or °C/W	This is the thermal impedance posed by the motor to the ambient.
Thermal Time Constant	τTH	min	Time constant based on the thermal impedance. A motor with a heat sink will have a higher time constant than a motor without a heat sink.

Appendix 3

ACO Algorithm

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Ant Colony Optimization for Traveling Salesman Problem (TSP)   %
% Programmed By: SIAW KAH JING%
% This program runs correctly for a full graph. In a full graph all nodes are
connected to each other. %

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all
clc;

%Sample Kp, Ki, Kd Matrix
no_sample_Kp = 51;
no_sample_Ki = 21;
no_sample_Kd = 21;

sample_parameter_p(1,1)=0;
for row=2:no_sample_Kp
    sample_parameter_p(row,1)=sample_parameter_p(row-1,1)+0.2;
end
```

```
   sample_parameter_i(1,1)=0;

 for row=2:no_sample_Ki


   sample_parameter_i(row,1)=sample_parameter_i(row-1,1)+0.5;

 end


   sample_parameter_d(1,1)=0;

 for row=2:no_sample_Kd

    sample_parameter_d(row,1)=sample_parameter_d(row-1,1)+0.05;

 end

%ACO Starts

ant_population_p = no_sample_Kp;

ant_population_i = no_sample_Ki;

ant_population_d = no_sample_Kd;

ise_best = 999999999;


for k=1:ant_population_p

    Kp = sample_parameter_p(k);


    for n=1:ant_population_i

        Ki = sample_parameter_i(n);
```

```
    for x=1:ant_population_d
        Kd = sample_parameter_d(x);

        %Compute function value
        simopt =
simset('solver','ode5','SrcWorkspace','Current','DstWorkspace','Current');% Initialize
sim options
        [tout,xout,yout] = sim('optsim1',[0 50],simopt);

        %Compute the error
        e=yout-1;

        %Compute the overshoot
        sys_overshoot=max(yout)-1;
        sys_shoot = abs(sys_overshoot);

        alpha=10;
        beta=10;
        ise(k,n,x)= e2*beta+sys_shoot*alpha;
```

```
            if ise(k,n,x)<ise_best
                ise_best = ise(k,n,x);
                Kp_best = sample_parameter_p(k);
                Ki_best = sample_parameter_i(n);
                Kd_best = sample_parameter_d(x);
            end
        end
    end
end

%report
Kp = Kp_best
Ki = Ki_best
Kd = Kd_best
```

Appendix 4

Recognition of The Project

UNIVERSITI TEKNOLOGI PETRONAS

SCIENCE&ENGINEERING DESIGN EXHIBITION

Certificate of Participation

This certificate is awarded to

SIAW KAH JING
890613-13-5985

in recognition of his contribution as

Participant of
Open Innovation Challenge

"Silver"

in the 29th edition of

SCIENCE AND ENGINEERING DESIGN EXHIBITION
UNIVERSITI TEKNOLOGI PETRONAS

held on
17-18 April 2012

Mohd Zamri B Abdullah
Chairman
29th Science and Engineering Design Exhibition

Prof. Ir Dr. Ahmad Fadzil B Mohamad Hani
Deputy Vice Chancellor , Academic
Universiti Teknologi PETRONAS

SEDEX