A PARTICLE SWARM OPTIMIZATION APPROACH FOR THREE PHASE LINEAR GENERATOR

Rajendran Sinnadurai[1], C.M Ting[2] and Qaslun Basheer Bin Hadi[3]

[1,2&3]*Faculty of Engineering and Life Sciences, Department of Engineering, University of Selangor, Malaysia*
E-mail: rajendran@unisel.edu.my, cmtingsteffi@unisel.edu.my & qaslun_hadi@ymail.com

Abstract

Particle swarm optimization (PSO) algorithm is applied for modeling three phase linear generator (TPLG). The objective of optimization is to maximize the performance of TPLG by keeping the cogging force at minimum value. The air gap length, magnet length, tooth width and magnet thickness are chosen as an optimization variables. Finite Element Method Magnetic (FEMM) will be used to verify the result of optimization. Finally, by using an AC-AC converter, the output voltage of TPLG will be stabilized. This can be done by using the Matlab Simulink.

Keywords: Particle Swarm Optimization, Three Phase Linear Generator, Cogging Force and Finite Element Method Magnetic.

1 INTRODUCTION

Particle Swarm Optimization (PSO) is a numerical search algorithm that was introduced by Kennedy and Eberhart in 1995, inspired by social behaviour of bird flocking or fish schooling. R. Jacob introduced the conceptual overview and detailed explanation of the PSO algorithm in his paper by using a swarm of bees as analogy (Robinson & Rahmat-samii, 2004). PSO has been used in some researches to solve engineering problems such as optimizing the design of a linear brushless permanent magnet motor by C.Lucas (Lucas & Tootoonchian, 2010).

A three phase linear generator (TPLG) can be used as a sea wave energy converter. It converts the mechanical energy into electrical energy. TPLG has less mechanical interface and it's structure is simpler over the conventional rotary generator. This would reduce the use of fossil fuel, as sea wave energy is renewable (Santosh Kumar, Krishna, Ranjan, & Dubey, 2015).

Like other linear machines, sea wave energy converter presents some drawbacks. One of the major concerns with linear generator is the cogging force that results from the interaction between the permanent magnets mounted on the translator with back iron and teeth (Gargov, Zobaa, & Pisica, 2014; Ivanova, Ågren, Bernhoff, & Leijon, 2004; Member, 2003). Such interaction can result in excess noise and vibration as well as unintended latching effect on the translator (Brauer & Ziolkowski, 2006; Prudell, Stoddard, Amon, Brekken, & Von Jouanne, 2010). To reduce the cogging force in TPLG, several techniques such as shaping and slotting have been studied. Researchers from (Faiz, Ebrahimi-Salari, & Shahgholian, 2010) and (Trapanese, Cipriani, Curto, DI DIo, & Franzitta, 2016) have shown that the cogging force can be reduced by decreasing the permanent magnet length and increasing the air gap length.

In this paper, PSO method is implemented by using Matlab and applied to four different parameter of a TPLG. These four parameters are defined as the optimization variables. The TPLG is modeled using FEMM. The output of the TPLG will be stabilized and connected to national grid.

2 COGGING FORCE REDUCTION BY USING PSO

The PSO is initialized with a collection of random particles (solutions) and the optimum is determined by updating the generations. The particles move through the solution space, and they will be evaluated according to some fitness criteria after each time step. In every iteration, each particle is updated by following two "best" value. The first one is the best solution that has been achieved so far. This value is known as pbest. Another "best" value that is tracked by the particle swarm optimizer is the best value obtained so far by any particle in the population. This second value is known as a global best and called gbest. When a particle takes part of the population as its topological neighbours, the second best value is known as local best and called lbest. After searching for these two best values, the particle will updates its velocity and positions using the following equation (Settles, 2005):

$$v_{id}(t) = w(t) * v_{id}(t-1) + c_1 * rand() * (\rho_{id} - x_{id}(t-1)) + c_2 * Rand() * (\rho_{gd} - x_{id}(t-1)) \quad (1)$$

$$x_{id} = x_{id} + v_{id} \quad (2)$$

where:
t = current time step, t-1 = previous time step
$v_{id}(t)$ = current velocity at site d of individual i.
ρ_{id} = individual's i best state (position) found so far at site d.

ρ_{gd} = neighbourhood best state found so far at site d.
c_1 = social parameter 1, a positive constant, usually set to 2.0.
c_2 = social parameter 2, a positive constant, usually set to 2.0.
rand () = a positive random number drawn form a uniform distribution between 0.0 and 1.0.
Rand () = a positive random number drawn from a uniform distribution between 0.0 and 1.0.
$w(t)$ = inertia weight (Inertia Particle Swarm)

The pseudo codes of the above procedures are shown in Figure 1 (Settles, 2005) :

```
For each particle
    Initialize particle
END
Do
    For each particle
        Calculate fitness value
        If the fitness value is better than the best fitness value (pBest) in history
            set current value as the new pBest
    End
    Choose the particle with the best fitness value of all the particles as the gBest
    For each particle
        Calculate particle velocity according equation (1)
        Update particle position according equation (2)
    End
While maximum iterations or minimum error criteria is not attained
```

FIGURE 1: Pseudo codes

The pseudo codes above can be represented as a flow chart as shown in Figure 2.

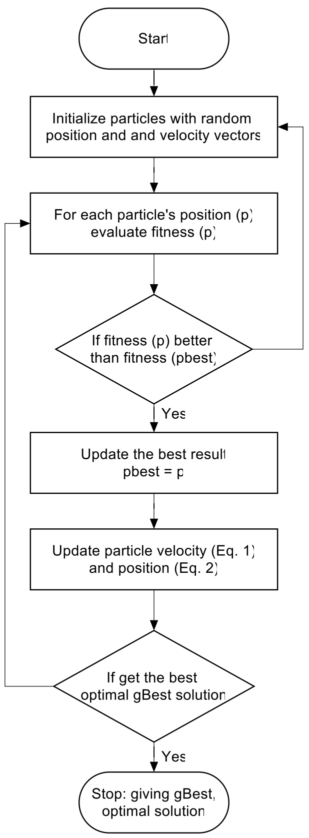

FIGURE 2. Flowchart of the PSO (Robinson & Rahmat-samii, 2004)

Figure 3 shows the cross-sectional model of the TPLG in Finite Element Method Magnetic (FEMM). Table 1 shows the parametric specifications of TPLG that had been assumed and calculated. The output voltage, output power and cogging force are tabulated in Table 2. The maximum cogging force for TPLG is 1500 N.

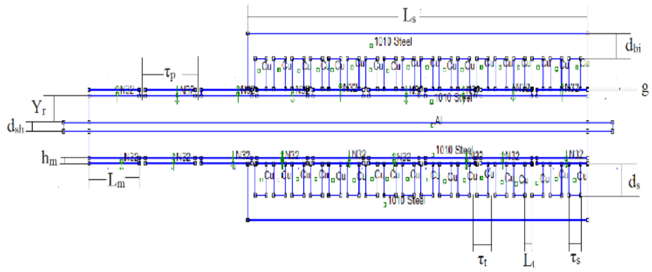

FIGURE 3. Cross-sectional model of TPLG

TABLE 1. Parametric specifications of TPLG

Part	**Materials**	**Dimensions and properties**
Stator core	1010 Steel	μ_r = see BH curve Stator Width, W_s=132 mm Stator Length , L_s = 533 mm Slot Opening, τ_s =18 mm Slot Height, d_s = 34 mm Tooth Pitch, τ_t = 29 mm Tooth Width, L_t = 11 mm Back Iron Thickness , d_{bi} =28 mm
Translator core	1010 Steel	μ_r = see BH curve Pole Pitch, τ_p = 88 mm Rotor Yoke, Y_r=30 mm
Permanent magnet	NdFeB N32	B_r = 1.15 T H_c = 883310 A/m Magnet Thickness, h_m =6 mm Magnet Length, L_m =79 mm Magnetization direction: radial (outward and inward)
Shaft	Aluminium, 1100	μ_r = 1 Shaft Diameter, d_{sh} = 10 mm
Air gap		Air Gap Length, g = 1 mm
Winding	Copper	SWG#10 μ_r = 1 Wire Diameter, D_w =3.25 mm Number of turns, N_c =40 turns

TABLE 2. Output power (kW) and cogging force (N)

	Rms Value (V)		**Output Power (kW)**
emfRed	707.5	P_A	29.361
emfYellow	411.5	P_B	17.077
emfBlue	355.2	P_C	14.74
	Total Power	$P_A+P_B+P_C$	**61.2**
	Cogging Force		**1500**

Four parameters of TPLG as shown in Table 3 have been chosen for optimization. The boundary values that are the lower and upper boundary are the minimum and maximum size of the parameters that have been chosen randomly.

TABLE 3. Optimization variables and boundary values

Variable	Parameters	Lower Boundary	Upper Boundary
X1	Air gap length, g	1 mm	1.5 mm
X2	Magnet length, L_m	79 mm	82 mm
X3	Tooth width, L_t	11 mm	14 mm
X4	Magnet thickness, h_m	4 mm	6 mm

The total induce electromagnetic force, (emf) induced by TPLG according to C.Mademlis and I.Kioskerisdis is shown in Eq. 3 (Mademlis, Kioskeridis, & Theodoulidis, 2005) where the emf , e is proportional to the translator velocity, v and to the rate of change of the machine's inductance with its position $\left(\frac{dL}{dx}\right)$.

$$e = v\frac{dL}{dx} \tag{3}$$

The translator velocity depends on the structure of the generator. The inductance depends on the structure configuration of the TPLG. For different relative positions of the translator, in respect to the stator, the generator will assume configurations with particular values of inductance.

Thus, each structural configuration will present inductance values between a maximum and a minimum value. The greater the difference between the value of inductance in the alignmed position (L_a) and the inductance value in the unaligned position (L_u), the greater will be the emf developed at terminal of electric phase of the generator for a given velocity of the translator. Likewise, the smaller is the distance (Δx), the smaller will be the developed emf.

Eq. 4 shows the factor Q, which represents the linear rate of change of the inductance with its position of the translator between the aligned and unaligned position.

$$Q = \frac{L_a - L_u}{\Delta x} \tag{4}$$

The factor Q was set as the objective function in the Matlab script as an ".m file" for optimization process as shown in Figure 4. The rate of change of inductance in the above equation was found using the FEMM simulation, and the value is 0.332 H.

Figure 5 below shows a part of the Matlab's coding for PSO operation. The LB and UB represented the lower boundary and upper boundary of the variables. This PSO will run a maximum 10 times with a maximum of 1000 iterations.

```
function f=ofun(x)

% objective function (minimization) / factor Q
of=0.322/(x(1)-x(2));

c0=[];
c0(1)=x(1)+x(2)+x(3);

for i=1:length(c0)
    if c0(i)>0
        c(i)=1;
    else
        c(i)=0;
    end
end
penalty=10000;
f=of+penalty*sum(c);
```

FIGURE 4. Objective function of Q factor

```
LB=[1 79 11 4];         %lower bounds of variables
UB=[1.5 82 14 6];       %upper bounds of variables

% pso parameters values
m=4;                % number of variables
n=100;              % population size
wmax=0.9;           % inertia weight
wmin=0.4;           % inertia weight
c1=2;               % acceleration factor
c2=2;               % acceleration factor

% pso main program----------------------------------------
maxite=1000;    % set maximum number of iteration
maxrun=10;      % set maximum number of runs need to be
for run=1:maxrun
    run

    % pso initialization----------------------------------
    for i=1:n
        for j=1:m
            x0(i,j)=round(LB(j)+rand()*(UB(j)-LB(j)));
        end
    end
```

FIGURE 5. PSO coding in Matlab

3 AC-AC CONVERTER

An AC to AC converter is a power electronic converter that converts AC waveform into another AC waveform where the output voltage and frequency can be controlled. In this paper, a traditional AC-AC converter, which is a pulse width modulation (PWM) voltage source inverter (PWM-VSI), is used to control the output voltages of TPLG and this can be done by using Matlab Simulink. As shown in Figure 6, PWM-VSI consists of two converter stages and an energy storage element (RC filter), which convert the TPLG's output phase voltage (AC waveform) into DC by using full-bridge rectifier, and reconvert the DC back into AC waveform by using three phase inverter. Six diodes (1N4007) and six MOSFET were used for rectifier and inverter stage respectively. The AC output can be controlled by modulating the duty cycles of the MOSFET (Szcześniak, 2013). The ripple factor for this circuit is chosen to be 0.01 (1%). Therefore the value of smoothing capacitor, C and resistor, R for RC filter is 63 mF and 16 Ω respectively. The modulation index of Pulse Width Modulation (PWM) was set to 0.54.

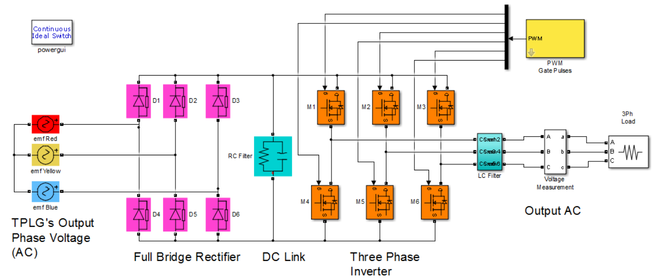

FIGURE 6. Three Phase AC-AC converter (Daniel W.Hart, 2011; Szcześniak, 2013)

4 RESULT

The optimize result of the PSO from the Matlab simulation is shown in Table 4. Since the optimal value of PSO is same as the assumed and calculated values, therefore it can be concluded that the TPLG has the best parametric specification and performance where the cogging force is 1500N. Therefore, a verification by using FEMM is not necessary for this case.

TABLE 4. Parameter values before and after PSO

Variable	Parameters	Assumption/ Calculated Value	PSO Optimization Value
X1	Airgap length, g	1 mm	1 mm
X2	Magnet length, L_m	79 mm	79 mm
X3	Tooth width, L_t	11 mm	11 mm
X4	Magnet thickness, h_m	6 mm	6 mm

The final model of TPLG gives an output voltage of 707.5 V, 411.5 V and 355.2 V for emfRed, emfYellow and emfBlue respectively. Hence by using an AC-AC converter, these voltage values can be controlled and stabilized. Figure 7 represents the three phase output voltages of TPLG in AC waveform before rectification.

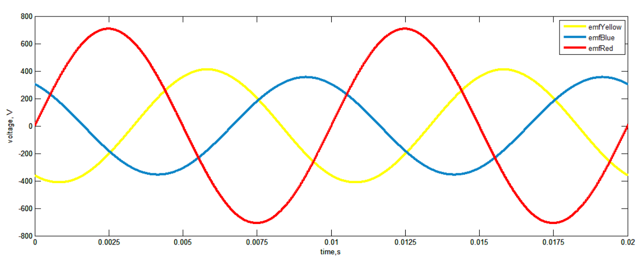

FIGURE 7. TPLG's output voltage before rectification

The full-bridge rectifier then will convert the AC waveform into DC waveform as shown in Figure 8. The value of RC filter is important since it will determine the ripple factor of the waveform. It can be seen that the waveform after rectification is almost purely DC because the ripple factor is only 1%.

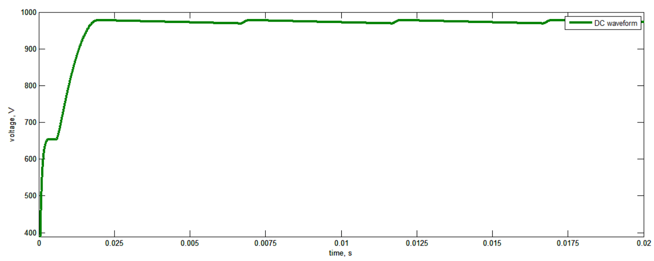

FIGURE 8. DC waveform after rectification stage

Figure 9 represents the waveform after the second stage, where the DC waveform was reconverted into three phase AC waveform. By changing the modulation index of PWM to 0.54, the rms voltage for all phases of TPLG are approximately 415 V as compared to the initial rms voltage shown in Figure 7.

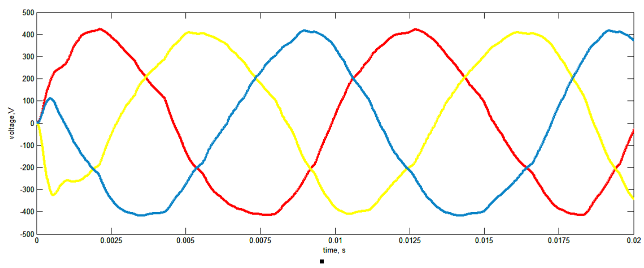

FIGURE 9. TPLG's output voltage by using AC-AC converter

5 CONCLUSION

The PSO approach to the TPLG modeling has been presented. From this approach, the optimal value for the air gap length, magnet height, magnet width and tooth width of the TPLG have been found. The output of the PSO has been validated with the help of FEMM. The optimization values show the same values as calculated. The AC-AC converter has been used to control and stabilize the output voltage of TPLG. The three phase output voltages have been stabilized to 415 V. The result has been successfully achieved.

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