Design Optimization of PMSM with Temperature Effect using GSA and GSA-PSO

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Abstract: The design of the machine is complex and regrous process. There are many parameters which influence the design of a machine. The manufacture has to keep an eye on these factors well in advance and consider their effect on the geometrical parameters. The research work focused on the temperature effect while optimizing the geometrical parameters of permanent magnet synchronous machine. The objective which is based on the minimization of temperature of the machine has been formulated. The optimization of geometrical parameters has been done using natured inspired Newtonian law based Gravitational Search Algorithm. This paper focused on a comparative study which has been done on algorithms and their hybridization of Gravitational Search Algorithm and Particle Swarm Optimization.

1 INTRODUCTION

World's technology is moving at a faster rate with lots of improvement in the manufacturing industries, maintained of electrical equipment's, use of electrical equipment in space science, biomedical instrumentation, electrical vehicle, communication industry, power utility etc. All this is possible because of the different types of machine. These different configuration of machine may be used in advance application as stated above. In these advance applications the machine is required to work in most extreme conditions. The manufacturer before manufacturing the machine consider all the factors which affects the working of the machine for desired performance. The factors which mostly affects the performance of the machine is temperature, skin effect, skewing, cogging torque, torque ripple etc. Among all the factors temperature is one of the major factor which affects the machine's performance. It has been seen many cooling techniques adopted by the manufacture to limit the temperature in the permissible limits while working in the extreme conditions without sacrificing the performance of the machine. The cooling methods adopted are natural air cooling, forced air cooling, gas cooling and oil cooling, etc. Therefore it is important to find the minimum working temperature with optimal geometrical parameters for set of desired performance of the machine.

There are several ways by which the temperature analysis have been done as temperature affects all parts from shafts to the frame of the machine the heat mostly developed in armature windings due to ohmic loss and in the core due to hysteresis and eddy current constituted core loss, friction also constituted the development of heat in the machine. In (Xyptras and Hatziathanassiou, 1999)the thermal analysis have been performed where cross-section of an asynchronous machine have been taken for evaluating the copper and iron loss at steady state and deep bar effect under transient conditions. Similar study have been performed while considering the totally enclosed fan cooled electric motor where steady state and transient conditions are used to estimate the temperature of the machine (Mellor et al., 1991).The online temperature estimation has also been done using thermo fluid model to predict the temperature in an oil cooled machine . This method has the accuracy up to 94% of the actual value(Camilleri et al., 2015). The temperature has also been estimated using high frequency current injection method in Permanent Magnet Machines(Reigosa et al., 2016). Some dynamic analysis have been performed for evaluating the real time analysis of thermal field effect using Finite Element

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model(Wang et al., 2019). As it is evident that the temperature affects the electrical machine in a way where it affects the performance of the machine. In (Husain et al., 2016; Le Guyadec et al., 2019) The temperature effect have also been taken into consideration in the design process. In (Madonna et al., 2018) the management in regulating the temperature of the electric machine have been done to find out the effective cooling methods and their comparative analysis. İn (Xue et al., 2018) an iron loss model for the electrical machine have been reviewed which helps in the temperature prediction of the machine. The machine can work in high temperature using super conductors with no insulation for the application of electric propulsion of aircraft(Wang et al., 2020).

There are following research which carried to incorporate the temperature effect while designing a machine (Bramerdorfer et al., 2018; Kreuawan et al., 2008; Mellor et al., 2014). In(Baker and Mellor, 2017)a design optimization have been done depending up on the split-ratio which balances stator iron and winding losses. This optimized design is successfully used for higher output power and higher with available volume. There are many methods developed for thermal analysis(Ayat et al., 2016)and considering the effects of degradation of the permanent magnets due to temperature effect(Sumislawska et al., 2016). New cooling method has also been reported in the literature where effect of spray parameters in heat dissipation have been effectively analyzed(Zhenguo et al., 2017).

The following points have been inferred while doing a short literature review on the temperature effect:

- Most of the research involved the analytical study of post effect analysis of temperature on the machine.
- The mitigation of the temperature rise problem can be done using several cooling methods including spray.
- Design of machine has also been reported in the literature while consideration different type of materials which helps in reducing the losses in the machine(Ismagilov et al., 2017; Persson and Jansson, 1995; Rahaman and Sandhu, 2019)

The literature review in the given domain has been carried and salient points have been enumerated. The author also pointed out some of the unsearched and dormant areas which are important in the manufacturing and designing of electrical machine are:

- The factors which affect the performance of the machine must be considered before manufacturing scare literature is reported in this direction.
- There a need to find a heuristic approach in finding the optimal geometrical parameters of the machine such that the performance as well as cost may not be compromised.
- The machine may be design for limiting value of the nonlinearities present like flux density, temperature, current density, frequency etc.

In this research work the author solved the design problem with the help of a natured inspired-Newtonian law based gravitational search algorithm (GSA).GSA is based on the law of gravitational forces and was enumerated by Rashedi in 2009 (Rashedi et al., 2009; Rashedi et al., 2011). In this optimization technique the solutions are having different parameters called masses in term of GSA. The obtained solution is a large aggregation of masses which exerts forces on each other. The solution having larger mass represents the optimal solution in the search space and it cannot be attracted by others small masses (Hassanzadeh and Rouhani, 2010). The GSA has already been used in solving problems like optimal power flow, economic dispatch and unit commitment (Duman et al., 2012; Mondal et al., 2013; Roy, 2013; Xing and Gao, 2014). In this research work the GSA has been hybridized with PSO. The temperature of the machine has been considered in finding the optimal geometrical parameters of the machine. These optimal geometrical parameters corresponds to the minimum temperature, maximum efficiency and minimum regulation. It seems to be possible that the optimal geometrical parameters of the machine is such that the temperature of the machine kept constant without affecting the performance of the machine.

The article has been structured in such a way that the objective function has been formulated while incorporating the possible geometrical parameters in section II. The heuristic algorithm have been studied in section III. In section IV the results pertaining to optimal evaluation of geometrical parameters of PMSM considering temperature effect using GSA and GSA-PSO.

2 GSA AND ITS HYBRIDIZATION WITH PSO

Here, the GSA and GSA-PSO are used to optimize the temperature of the machine. Their algorithms have been discussed here in the following section in detail.

2.1 GSA Algorithm

Step1: Let a system with 'n' number of agents and the position of the i^t agent is given by,

$$P_i = (p_i^1, \dots\dots p_i^d, \dots\dots p_i^n). \quad (1)$$

Step2: Evaluate the fitness of the objective function.

$$Fitness_i = f(p_i^1, \dots\dots p_i^d, \dots\dots p_i^n). \quad (2)$$

Step3: Both thegravitational and inertial mass depends upon the fitness of theobjective function and are given by,

$$M_{ai} = M_{pi} = M_{ii} = M_i, \quad (3)$$

$$m_i(t) = \frac{fitness_i(t) - worst(t)}{best(t) - worst(t)}, \quad (4)$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_j(t)}, \quad (5)$$

Here the fitness *(t)* is the fitness of the object *I* at time *t* and worst and bestfitness is given by,

$$bestfitness(t) = \min_{j \in (1 \dots\dots N)} fitness_j(t) \quad (6)$$

$$worstfitness(t) = \max_{j \in (1 \dots\dots N)} fitness_j(t). \quad (7)$$

Step 4: Calculate the force on mass *I* due to mass *j*.

$$F_{ij}^d = G(t) \times \frac{M_{pi}(t) \times M_{aj}(t)}{R_{ij} + \varepsilon} \times (p_j^d(t) - p_i^d(t)), \quad (8)$$

Here, M_{aj}acts as active mass of object *j*; M_{pi} is the passive mass of object *i*.

The R_{ij} *(t)* is given by,

$$R_{ij}(t) = \|P_i(t), P_j(t)\|, \quad (9)$$

Step 5: Calculate the total force acting on mas-$s_i F_{Ti}^d(t) = \sum_{j \in Kbest, j \neq i}^{N} rand_j \times F_{ij}^d(t)$, (10)

Here, *Kbest* is the set of initial *objects with* the best fitness.

Step6: Calculate the acceleration of mass *i* in time t in the d^{th} dimension is given as follows,

$$a_i^d = \frac{F_{Ti}^d(t)}{M_{ii}(t)}, \quad (11)$$

Step7: Update velocity and position as,

$$u_i^d(t+1) = rand_i \times u_i^d(t) + a_i^d(t), \quad (12)$$

$$p_i^d(t+1) = p_i^d(t) + u_i^d(t+1). \quad (13)$$

2.2 Algorithm for GSA-PSO

GSA-PSO combined the social thinking PSO with local search capability of GSA.

The steps 1 to 6 have been same except the update of velocity and position as,

$$u_i^d(t+1) = wu_i^d(t) + C_1 randa_i^d(t) + rand\,(Xgbest - X_i) \quad (14)$$

$$p_i^d(t+1) = p_i^d(t) + u_i^d(t+1). \quad (15)$$

3 PROBLEM FROMULATION OF PARAMETER ESTIMATION OF PMG

In this proposed research work, temperature is considered as main objective. The objective is to minimize the temperature of the machine while optimizing the values of the selected design variables i.e.D_o, D, L, h_s.

$$F(t) = min(Temp) \quad (16)$$

Formulatedmain objective function as,

$$Temp(D_0, D, L, h_s,) = \frac{7.92L + 3.188L(0.785(D_O^2 - D^2) - S \times 0.013 \times h_s)}{\left(\frac{\pi D_O L}{0.03}\right) + \left(\frac{\pi DL(1 + 0.1\pi D10)}{0.3}\right) + (17.5 \times \pi^2 \times D(D_O^2 - D^2)} \quad (17)$$

Where, D_o is outer diameter; D is air gap diameter; L is length of the machine; h_s is height of the stator slot.

Subjected to constraints as per given equations,

$$\eta_i^{min} \leq \eta_i \leq \eta_i^{max} \quad (18)$$

$$Reg_i^{min} \leq Reg_i \leq Reg_i^{max} \quad (19)$$

The performance parameters have been calculated using optimal values,

- Efficiency is calculated as per equation ,

$$\eta = \frac{P_o}{(P_o + iron_{loss} + copper_{loss})} \quad (20)$$

- Regulation is calculated as per equation,

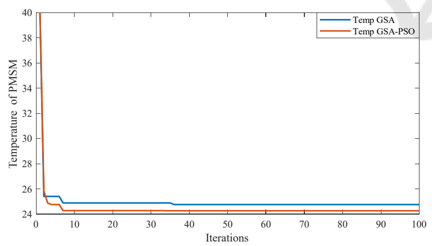
$$Reg_i = \left(\frac{E_o - E_{ph}}{E_{ph}}\right) \times 100 \quad (21)$$

4 RESULTS AND DISCUSSION

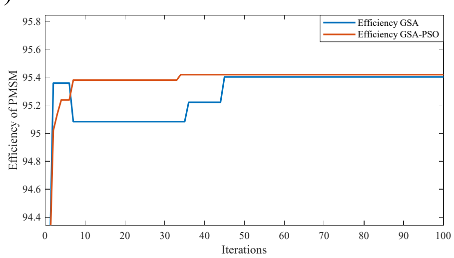
A 3.3kV, 500KVA, 3-phase, 50 Hz, 600 rpm,PMSM. The design parameters (D_o, D, L, h_s,) are evaluated while considering the temperature of machine as main objective. The function of temperature is optimized using GSA and GSA-PSO. The Table 1 shows the optimal results evaluated using both the algorithms.

Table 1: Effect of temperature on design parameters and performance of Machine

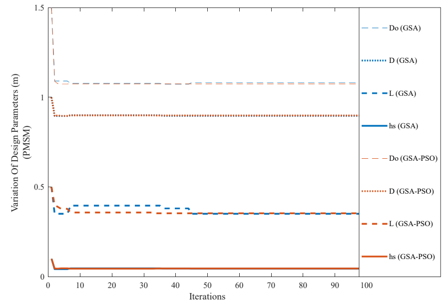
Design parameters	Range of parameters and Initial design parameters	Optimal design parameters using GSA	Optimal design parameters usingGSA-PSO
Outer diameters (m)	1.142-1.04	1.0780	1.0752
Air gap diameters (m)	0.9-0.8	0.8981	0.8986
Length (m)	0.45-0.35	0.3515	0.3533
Depth of stator slots, (m)	0.0475-0.0411	0.0466	0.04566
Performance Indices	Initial Indices	Performance	
Temperature (^oC)	33.266	24.355	24.2668
Regulation	32.12	31.745	31.7237
Efficiency	93.49	95.425	95.4186
Max flux density in the stator teeth. (wb/m^2)	1.92-2.1		1.5082



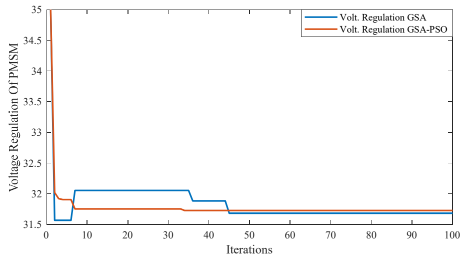
(a)



(b)



(c)



(d)

Figure 1: Performance optimized curves of temperature minimization function of PMSM using GSA and GSA-PSO: (a) Optimization curve of temperature using GSA and GSA-PSO. (b)Variation of efficiency as performance parameter of PMSM using GSA and GSA-PSO. (c)Variation of design parameters of temperature using GSA and GSA-PSO. (d) Variation of regulation as performance parameter of PMSM using GSA and GSA-PSO.

It is seen from table 1, the design variables are in their specified range and the performance of machine improves from initial design parameters. The temperature of the machine has been reduced by 26.78% and 27.05% using GSA and GSA-PSO respectively. The GSA-PSO has improved the reduction of temperature from GSA by 0.274%.

It has been reported in earlier results and in the optimizing curves that the GSA-PSO improves the results and quickly converges towards the optimal values than GSA. The regulation of the machine has been improved by 1.167% and 1.27% respectively. It has been seen in the table 1 that there is increase in efficiency of the machine by 2.06 %, using both algorithms.

The fig 1 (a) shows the temperature optimizations curve. The curve shows the initial variation but soon after approximately 45 iterations the curve settled to its optimal value. The variation of design parameters which are dependent upon the temperature has been shown in fig 1 (b). The improvement in the performance parameters of the machine like efficiency and regulation have been shown in fig 1 (c) and fig 1 (d)

5 CONCLUSION

In this research work an objective function pertaining to the design of PMSM has been formulated. The objective function is formulated taking into consideration the temperature effect. The geometrical parameter so obtained corresponds to minimum temperature, maximum efficiency and minimum regulation. Following important points have been inferred from this research work:

- The GSA and GSA-PSO both are capable of optimizing the objective function shows the versatility in optimizing different set of problems.
- While optimizing the problem using GSA the temperature is 24.35, efficiency is 95.4%, regulation is 31.7%.
- The results obtained from the GSA-PSO has also been similar like the temperature is 24.26, efficiency is 95.4% and regulation is 31.7%.
- While comparing both the algorithms the GSA-PSO although gives similar results but it converges faster as compared to GSA.

The GSA and GSA-PSO opens up the scope of designing a machine with desire performance.

6 FUTURE SCOPE OF WORK

The current research restricted up to the evaluation of geometrical parameters while considering the temperature effect. Further studies can be carried on the factors that affect the performance of the PMSM like demagnetization of permanent magnets, skin effect, skewing effect and cogging torque etc. Research can be extended while changing the material for manufacturing the machine which uses magnets of high magnetic flux density, hybrid materials to reduce the weight of the machine.

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