

OPTIMAL FIELD ORIENTED CONTROL OF MULTI-WINDING SYNCHRONOUS MACHINE USING FIREFLY ALGORITHM AND MULTILEVEL INVERTER - A REVIEW

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Abstract : *The synchronous machine is widely used machine in industrial power plants. It has both field and stator control. The three-phase synchronous machine is widely used but main drawback of that is the size of the machine and control complexity when the rating of the machine is increased. The speed control of the synchronous machine is done by field control, vector control and direct torque control. In vector control the flux and speed are controlled and the required speed is achieved in many loading conditions. The problem in the vector control is it depends on the parameter of the machine. The machine parameter affects the performance of the speed control. So optimum parameter selection is must in this case. In DTC control vector is complicated in multi-winding machine. To control the switches pulse generation is complex. The vector control of multi-winding machine is better to control when the parameters are optimally set. And multi-level inverters are used to reduce the size of filters and to reduce the total harmonic distortion. To get better performance with multi-level the phase opposition or phase disposition is used as the pulse generator. The application of multi-machine system is on ships and aircraft like dedicated applications. From the analysis it is found that the optimal SPSSG parameters can be selected by maximizing the efficiency of the machine by taking current limit, real and reactive power limits as constraints. Then the optimized six-phase machine is fed with the multilevel inverter. This drive setup is controlled with the field-oriented control. The PID controller used as the speed regulator. PID values are can be calculated by firefly algorithm by minimizing the steady state error , the response of the multi-winding machine improves the performance parameters like stability, loss minimization and efficiency improvement.*

Key Words: DTC, Vector Control, PID, DSSM(Double star synchronous machine), Firefly algorithm

1. Introduction

The power system consists of generation station, transmission and distribution. In the generating station synchronous machines are used generally. The induction machine uses induction as

the principle to share the power between stator and rotor. But the synchronous machine uses the permanent magnet or excitation of rotor coil for the flux production. It is named synchronous because the rotor rotates in phase with the flux generated by the stator currents. Various new types of synchronous generators are being developed like multi-pole machine for wind power conversion systems. These machines have the very important role to achieve a high efficiency and a reliable power system with good power quality. A detailed and accurate model is essential to investigate the performance of a synchronous machine and its control strategies. The generated power has to be supplied to the load. For that the control strategies use the switching devices and other devices, which has lesser power rating. The larger power rated devices are not available easily and it need heavy protection circuit.

The six phase synchronous machine is power full for power generation. The semiconductors have current limitations in the case of high power generation that is overcome by this machine. This type of machines has improved torque and MMF compared to three-phase. The six-phase machine can be used as the AC-DC generator where the six-phases can be rectified and used as the AC-DC generator. This type of AC to DC conversion can be applied to aircraft, ships as it is low weight and lesser filter is required. The fluctuation in energy transfer is reduced due to rotor inertia. When there is only DC supply available the DC motor/AC generator set can be used for lesser weight and maintenance. This six phase synchronous machine can be used as the input to air-conditioner in trains, which gets DC supply.

Another type of synchronous machine is brushless synchronous machines, Brushless direct current, BLDC machines which got popularity in recent years. The torque-speed characteristic of the

machines is equivalent to the brushed DC motors. The drawbacks of the mechanical commutations are not present in these types of synchronous machines. These machines have the permanent magnets on its stator. So the rotor coil and energization of the coil is not required. The windings in the stator are made up from many coils interconnected. The windings are then evenly distributed around the stator to form an even number of poles. Depending on the winding topology, the back emf (electromotive force) is either of sinusoidal shape or trapezoidal shape. These machines also can be made as six phase machines to reduce the problems in high power generation.

2. Literature survey

The articles related to the synchronous/asynchronous machines are dealing mainly with,

- Modeling of machines
- Field-oriented control
- Direct torque control
- Estimation of the parameters of the machines
- Fault identification of the machines.

Are taken for the survey to identify the research gap.

2.1 Modeling of machines

Schiferl RF in 1983, presented a detailed circuit representation of a six phase synchronous machine wherein mutual leakage couplings between the two sets of three phase stator windings are included. With sinusoidal inputs the main modes of power transfer of a six-phase machine are examined. The mutual leakage inductances with winding displacement angle relationship and pitch for a number of practical six-phase winding configurations are derived. The operating load conditions, winding displacement angle, pitch, converter commutating reactance, and rotor impedance with AC-DC stator connections are characterized in this article and a novel application of the six-phase machine in an uninterruptible power supply scheme is proposed.

Sudhoff SD in 1993, discussed the average value characteristics of 6-phase synchronous machine system with dual line commutated converter. Vetter W in 1994 has proposed the damper winding current of synchronous machine with a solid iron rotor. The model's component elements are determined by finite element method.

Singh GK in 2003, the stability of the multiphase induction machine is analyzed. The eigenvalue stability criterion is used in this article.

It is difficult get a change in machine parameter gives a change in machine parameters. This article made it possible. In 2011 he has modeled and analyzed the six-phase synchronous generator for standalone renewable energy generation. And in the same year the fabrication of the same six- phase machine is made and tested experimentally. In 2011 the transient analysis of isolated six-phase synchronous generator is made for different dynamic and loading conditions. And balanced and unbalanced loading condition with resistive, inductive and resistive-inductive is made and analyzed.

Cursino Brandao Jacobina in 2014 presented two-configuration system for six-phase synchronous system. One is with three phase series converters and three single-phase half bidirectional series converters and other configuration with full bidirectional converter. This configuration doesn't use the transformer for the step up. So the power losses are less.

2.2 Machine control techniques

2.2.1 Field oriented control

Vukosavic SN in 2005 has introduced the vector control of six-phase induction motor. Special attention is paid next to the current control issue, from the point of view of the minimum number of current controllers. Experiments are conducted with number of operating regimes, including acceleration, deceleration, reversing and step loading/unloading transients.

Martin Jones in 2006 has proposed the two motor drive system. Two topologies are used here. First one is the two asymmetrical connected in series and other uses one six phase and a two-phase ac machine. Performance wise the two asymmetrical machines performs better. The there is a problem with the connection of neutral point for this drive system.

Emil Levi in 2006 has presented a novel concept called multi motor drives on multiphase motors. Independent control of the motors can be achieved by connecting it in series combination. There is a problem when connecting the three-phase machine and six-phase machines in series due to the power flow from three-phase machine to six phase machine copper loss increases.

LazhariNezli in 2010, has presented the vector control of double star synchronous machine fed by three-level inverters controlled by PWM hysteresis strategy. The regulation of the chopper is made for rotor current control. And there is an added note on the replacement for the PI regulator

with recent control can perform still more.

Mario J Duran in 2010, presented a two series connected three-phase inverter and a grid side neutral point clamped multilevel inverter. Compared with back-to-back NPC converter this topology does not require the medium voltage generator. It has several advantages like improved power quality, increased efficiency, easier grid code compliance and smaller cables.

Paul Sandulescu in 2014, presented three models, first model has problems with triplen harmonics. Second have problems with optimal value predictions. The third model utilizes the DC link better and prevents zero sequence voltage in inverter saturation. And main thing to note in this article is the performance depends on the parameters of the machine. So machine design is necessary for the better performance. So these are all not done for the multi-machine systems.

2.2.2. Direct Torque control

KhezzarA in 1998 presented Current inverter fed synchronous machine which affects the torque ripple suffers damping losses. The suggestions given are by increasing number of phases this can over come.

Johan Bjork-Svensson in 2007 has submitted the thesis on the Torque control of a wind turbine using a 6-phase synchronous generator and also with DC/DC converter. The generator performs well with the low wind speed also.

Ibrahim Abuishmais in 2008 presented the analysis of redundant switch of the higher rating converters in the multiphase machines. The DTC control strategy with redundant switch analysis is also made and done with the fault condition of 4-phase fault. The sensitivity study of design parameters showed the possibility to optimize the machine gaining a higher efficiency level by reducing some of the losses. Redundancy analysis showed the possibility of operating the machine at half load when one supply system is totally or partially lost without exceeding machine's total losses. There is a lead to the next work that multi-machine optimization combined with converter optimization can also be done.

Boudana D in 2008 has presented DTC control on double star synchronous machine with fuzzy logic control for improving the performance. Due to fuzzy used in place of hysteresis the torque ripples are reduced. In 2009 using matlab graphical user interface the same control is applied with PI control.

Badreddine NAAS in 2012 DTC control of

double star permanent magnet synchronous machine is done by replacing the PI controller with sliding mode control. Compared with PI sliding mode control performs better.

Navid R. Abjadi in 2014 has presented a sliding mode control of two parallel or series connected induction machine. This article presents the torque and flux independent control and performances.

2.3. Parameter Estimations

Niewierowicz T in 2003 has discussed that the order of equivalent circuit increases the optimization index used in the identification procedure is enhanced in a clear fashion. To correctly reproduce the standstill frequency response data, this analysis is important for determining the number of rotor branches. The optimization is done by hybrid genetic algorithm.

Rafael Escarela-Perez in 2004 has studied the variation of synchronous machine parameters due to saturation. A hybrid genetic algorithm, capable of finding global extrema is then applied to obtain the parameters of two equivalent circuit structures for the d -axis. synchronous machine short-circuit and the results obtained have been compared to those calculated by a transient finite-element program.

Arjona MA in 2012 has presented the parameter estimation of the synchronous generator using standstill step voltage test. The hybrid genetic algorithm is used as the solution method. The three-phase short circuit test is used to finding the betterment of the responses.

SaeedehHamidifar in 2014, aims to develop a new synchronous machine model incorporating an accurate saturation model. The algorithm used in this article to represent magnetic saturation calculates the coefficients in several real function expressions for the saturation characteristics of a synchronous machine. It is also tested in various operating conditions.

2.4 Fault Identification and preventive measures

Sherif Omar Faried in 2002 has presented the impact of six phase transmission line faults on turbine-generator shaft torsional torques. And also subsequent fault clearing and reclosing on the torsional torques induced in the machine shaft. The studies conclude that six-phase transmission line faults generally induce torsional torques in the turbine-generator shaft whose magnitudes are relatively higher than those induced due to transmission line faults in a three-phase system.

Yaw D Nyanteh in 2013 has discussed the

fault diagnosis in permanent magnet synchronous machines using artificial neural network. The comparison between the neural network and the particle swarm optimization on the diagnosis is also made.

2.5 Tuning of PID controllers

Omar Bendjeghaba in 2014 has presented an article on the tuning of PID controller using continuous firefly algorithm for automatic voltage regulator system. And the performance increases due to the application of this new algorithm for tuning. SudhakarA in 2012 presented a paper on the comparative analysis of PI controller with Neuro Fuzzy on the Direct torque control application. Srinivasamurthy in 2013 has presented the performance comparison of Fuzzy and artificial neural network applied to direct torque control of induction motor. Jose L. Azcue in 2012 has introduced self tuning PI-type fuzzy applied to direct torque control to improve the performance of the induction motor control.

Olympia Roeva in 2013 has presented firefly algorithm based PID tuning applied to Glucose concentration control. Iztok Fister in 2013 presented a review of firefly algorithm. Nortin NM has discussed about the fuzzy-PI control applied to torque control and flux control for DTC with multilevel inverters of Induction motor. Turki Y Abdulla in 2010 has presented fuzzy logic based speed control of Direct torque control. And to minimize the torque ripple in the DTC fuzzy mode duty cycle also presented. Kumanan D in 2013 discussed on tuning of PID controller with firefly and compared with the Ziegler-nichols method. Ali ES in 2015 has discussed about the Firefly algorithm based speed control of DC series motor. Compared with genetic algorithm firefly algorithm provides better control.

Priyadharshini S in 2014 has proposed the tuning of PI controller with firefly algorithm applied for four area inter connected system for better performance. Gadoue SM in 2009 has presented artificial intelligence based speed control of DTC induction for improving the performance of the induction motor performance. Sweet Jose P in 2011 has presented the performance improvement of DTC with fuzzy logic. Hao Li Qiuyun Mo in 2010 has presented the fuzzy adaptive PI controller tuning for DTC control and to produce the better performance. Kandasamy M in 2014 has presented a paper on the PID tuning with firefly and bacterial foraging algorithm to make the performance better.

MohitBhagat in 2015 discussed the hybrid optimization technique for tuning PID controller with firefly combined particle swarm optimization. Shady M Gadoue in 2009 has presented the fuzzy and PI tuning with genetic algorithm for performance improvement of the direct torque control. Hakan Acikgoz in 2013 discussed about the PI controller and reduced rule base fuzzy for DTC and comparative analysis on the same. By referring the above discussions the PID tuning improvement can improve the performance of the entire system. The six-phase synchronous machines performance can be improved by using the optimal tuning methods. Here we chose firefly algorithm as in many literature this method is used and succeeded.

3. Research-gap Identification

3.1 Modeling of machines

The modeling of the machines has many articles and many researches are found in that area. So the new model of any multi-machine system may not provide an impact on the research much. But even though way of representation of the circuits can be done.

3.2 Field oriented control

- There are problems with the connection of neutral point for the drive system in two motor drive systems.
- When connecting the three-phase machine and six-phase machines in series due to the power flow from three-phase machine to six phase machine copper loss increases.
- The replacement for the PI regulator with recent control can perform still more.
- The performance of vector control depends on the parameters of the machine. So machine design is necessary for the better performance. So these are all not done for the multi-winding systems.

3.3 Direct Torque control:

- Less works are done for direct torque control of multi winding system.
- The identification of fault in the multi-winding and multi level inverter is lagging in the scientific articles.
- As the number of phases are more number of switches are also more and it is complicated to identify the fault in it. So techniques to identify and correct the fault are also lagging in the recent articles.
- Multilevel inverter controlled direct torque control is not presented in many literatures.

- Replacing the PI control with robust control or with any recent regulators is not made.
- The tuning of PI or PID parameters with intelligent algorithms are also not done in many articles.

3.4 Fault Identification:

- Many fault identification articles are available but all are with mainly on genetic algorithm or hybrid genetic algorithms.
- Many recent algorithms perform better in fault identification problems.

4. Problem Formulation

4.1 Parameter Optimization of multi-winding Synchronous machine

As per the above chapter the parameter optimization is important in the field-oriented control of induction machine. In this research the parameter optimization of the multi-winding synchronous machine is proposed to get better performance of the synchronous machine. The problem related to parameter optimization is important as the dimension of the problem increases. So the performance is taken as objective function and the maximization of the performance parameter like efficiency improvement or reduction of loss is taken as

The objective function is

$$\text{Maximize } \eta = \frac{P_o}{P_{in}} \dots \dots \dots (1)$$

Here,

η – efficiency of the machine

P_o – Output Power of the synchronous machine

P_{in} – Input power of the machine

Constraints:

Current limit

$$I_{abcxyz \min} \leq I_{abcxyz (rated)} \leq I_{abcxyz \max} \dots \dots \dots (2)$$

$I_{abcxyz \min}$ – minimum abcxyz phase current

$I_{abcxyz \max}$ – maximum abcxyz phase current

$I_{abcxyz (rated)}$ – rated abcxyz current

Real power limit:

$$P_{min} \leq P_{rated} \leq P_{max} \dots \dots \dots (3)$$

P_{min} – minimum real power of the machine

P_{max} – maximum real power of the machine

P_{rated} – rated real power of the machine

Reactive power limit

$$Q_{min} \leq Q_{rated} \leq Q_{max} \dots \dots \dots (4)$$

Q_{min} – minimum reactive power of the machine

Q_{max} – maximum reactive power of the machine
 Q_{rated} – rated reactive power of the machine

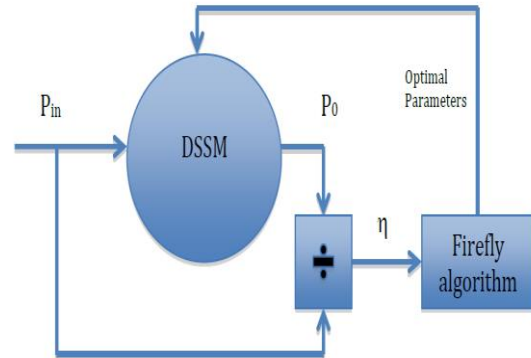


Fig 1. Parameter optimization of six-phase synchronous machine

The objective function is maximized using the firefly algorithm, which performs better compared to the particle swarm optimization algorithms used in the many literatures. And the comparison of the performances with cuckoo search algorithm, which makes 100% success rate, compared to particle swarm optimization and genetic algorithm.

4.2 Field Oriented control of parameter optimized six-phase synchronous machine with improved performance using PID parameter optimization and multilevel inverter

The field-oriented control of optimized parameter multi-winding synchronous machine with multilevel inverter to improve the entire performance of the synchronous machine is analyzed in this research. The efficiency improvement and loss reductions are the main key feature of this research. The block diagram of the proposed method is show below,

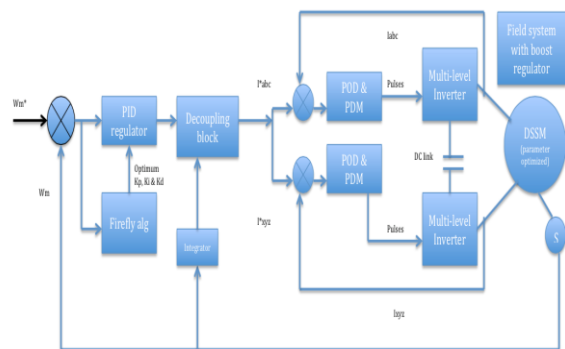


Fig.2. Field-oriented control of parameter optimized six-phase synchronous machine with multilevel inverter and optimal parameter selection of PID regulator.

The vector control of the six-phase synchronous machine has the problem of the response time. If there is a disturbance in the system it may take time to settle down. As this problem is over come by the direct torque control the control is complicated. This research makes the minimization of the steady state error, which may increase the stability of the entire system, is proposed. Many researches discusses about the parameter optimization with particle swarm optimization. But in this research uses the firefly algorithm, which is doing better than the conventional methods like particle swarm optimization is done. The comparison of the performance is done with the cuckoo search algorithm.

The objective function is stated below, minimize,

$$\text{Steady state error} = \text{mean}(\sum_{i=1}^n (W_m^* - W_m)) \dots (5)$$

W_m^* – reference speed in RPM
 W_m – Measured speed in RPM

This objective is minimized for obtaining the better performance of the entire field oriented control of synchronous machine.

4.3 Objective function

stated below,

Maximize,

$$\text{Power}(r_f, r_{kq}, r_{kd}) = \text{mean}(\sum_{i=1}^n P_m) \quad (1)$$

P_m – Measured power at grid in Watt

Constraints,

$$r_f^{\min} \leq r_f \leq r_f^{\max} \quad (2)$$

$$r_{kq}^{\min} \leq r_{kq} \leq r_{kq}^{\max} \quad (3)$$

$$r_{kd}^{\min} \leq r_{kd} \leq r_{kd}^{\max} \quad (4)$$

Here,

r_f – Fieldresistance

r_f^{\min} – minimumfieldresistance

r_f^{\max} – maximumfieldresistance

r_{kd} – Directaxisdampingresistance

r_{kd}^{\min} – minimumdirectaxisdampingresistance

r_{kd}^{\max} – maximumdirectaxisdampingresistance

r_{kq} – Quadratureaxisdampingresistance

r_{kq}^{\min}

– minimumquadratureaxisdampingresistance

r_{kq}^{\max}

– maximumquadratureaxisdampingresistance

This objective is maximized for obtaining the better performance of the entire field oriented control of synchronous machine.

4.4 Pseudo code for Firefly Algorithm.

Many fault identification articles are available but all are with mainly on genetic algorithm or hybrid genetic algorithms. Firefly algorithms perform better in fault identification problems.

The light intensity thus attractiveness is inversely proportional with the particular distance r from the light source. Thus the light and attractiveness is decrease as the distance increase.

$$I(r) = I_0 e^{-\gamma r^2}$$

I = light intensity,

I_0 = light intensity at initial or original light intensity,

γ = the light absorption coefficient

r = distance between firefly i and j

Attractiveness is proportionally to the light intensity seen by the another fireflies, thus attractiveness is β

$$\beta = \beta_0 e^{-\gamma r^2}$$

β_0 = Attractiveness at r is 0

The distance between two fireflies can define using Cartesian distance

$$r_{ij} = |x_i - x_j| = \sqrt{\sum_{k=1}^d (x_{i,k} - x_{j,k})^2}$$

Firefly i is attracted toward the more attractive firefly j , the movement is defined as

$$\Delta x_i = \beta_0 e^{-\gamma r_{ij}^2} (x_j^t - x_i^t) + \alpha \varepsilon_i, \quad x_i^{t+1} = x_i^t + \Delta x_i$$

4.5 Conclusion

In Six-phase synchronous machine field oriented control can be done by Firefly, CSA and PSO algorithm to increase the power transfer from the machine, which further increases the efficiency of the machine. Since the output power of the machine is depending on field resistances, direct and quadrature axis resistance of damper winding, the variation in these parameters gives better performance of the output power of the machine. So far Genetic algorithm and Fuzzy is used in this field of work, it is reviewed and found that FF, CSA and PSO will yield better performance for the analysis of Six-Phase Synchronous machine parameters which can be effectively implemented to renewable energy generation.

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