OPTIMIZATION OF A VOLTAGE SOURCE INVERTER FED SQUIRREL CAGE INDUCTION MOTOR

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Abstract
The paper deals with the design optimization of voltage source inverter (VSI) fed squirrel cage induction motor. A set of nine independent variables were selected and to make the machine feasible and practically acceptable, certain constraints were imposed on the design. Different objective functions were considered, namely, the active material cost, operating cost, a mixed objective function of the active material cost and operating cost, and the torque pulsation, to facilitate a suitable design for a given application. In these investigations the sequential unconstrained minimization technique (SUMT) with interior penalty function approach in conjunction with Rosenbrock's method of rotating coordinates was used to optimize the design. The optimized design results of a 7.5kW, delta-connected, voltage source inverter fed cage motor were given and discussed in detail.

KEY WORDS: Design Optimization, Motor Drive, Induction Motor, Torque Pulsation.

1 Introduction

The widespread implementation of variable speed drive has become a challenge for designers to achieve a machine fit for variable speed applications. The squirrel cage induction motor has special mechanical and electrical features which make it an economical proposition for variable speed drive. Using sources of variable voltage and variable frequency a cage induction motor can be operated with load-torque characteristics similar to those of DC motors, with the added advantages of ruggedness and maintenance free operation. For the inverter fed cage motor, the conventional design process has to be modified so that the resulting motor with improved performance becomes a strong competitor to the DC motor.

Some important and strategic applications of variable speed motors are in electric traction, the textile industries, and machine tools, the grinding and steel industries. Hence, because of cost considerations and many engineering constraints, the need for the optimized design of a variable speed induction motor arises. The variable speed cage induction motor drive [1-4] result n many problems, such as additional losses due to harmonics, and torque pulsation in the drive; hence the stability of the drive must be justified based on these factors. The factor behind this problem is that solid state variable frequency power supplies provide a source of power rich in harmonics. The additional losses due to harmonics in the stator as well as in the rotor will not only decrease the efficiency of the drive but also result in a greater temperature rise, causing thermal stresses in the insulation and mechanical stresses in the rotor bars and end-rings of the motor.

The voltage source inverter (VSI) output contains various harmonics, hence the supply voltage harmonies have the following causes and effects on the performance of the cage motor.

i. Current and flux harmonics result in additional copper and iron losses. Because of these additional losses the temperature rise is higher and the efficiency of the drive also tends to decrease.
ii. Driving and braking torques are produced in the motor, depending on the order of the harmonics; hence the overall available average torque is reduced.
iii. Torque pulsation due to interaction between the various currents and fluxes reduces the available speed range. The detailed study of pulsating torque [5-8] shows that they are quite detrimental to the performance of the drive, especially in the low speed ranges. The stability problem is due to the fact that the air gap MMF produced by the VSI supply does not rotate smoothly, but jumps in steps of 60^0, thus causing a jerky motion of the rotor. The stability problem [6] is more serious in the low frequency range due to high oscillations.

The best possible way to overcome these problems, or to keep them within permissible limits, is to modify the design of the motor to match the inverter characteristics. Hence, the resulting system is suitable for variable speed operation and offers the desired level of performance.

In the present investigation, an optimal design of such a cage induction motor with a variable frequency non-sinusoidal voltage supply is considered, this modified design, when fed from the VSI, giving the desired performance over a wide range of frequencies. After reviewing the literature, it was found that little work has been done on the design of the VSI fed cage motor. Hence, in the present paper an attempt has been made to achieve a modified design of the motor suitable for VSI fed operation. For this, four different objectives function of these two, and the torque pulsation, in order to select an appropriate design of the motor for a particular application. These objective functions are of importance when designing the VSI fed cage motor to meet customer requirements, so that the design has easy access to the market. A set of nine independent variables has been judicially selected. These variables affect the objective functions or impose constraints on the design. To meet the desired starting, running and thermal performance, and also to make the design practically feasible, twelve constraints have been imposed on the design.

2 Design difference between the VSI fed cage motor and the conventional supply fed motor

The design of the VSI fed motor is essentially different from the conventional supply fed induction motor. Many criteria adopted in the design of the conventional supply fed motor become irrelevant to the design of the VSI fed motor. The different criteria for the conventional supply fed design of the motor are reviewed below and the required modifications for VSI fed motors are discussed.

(i) The VSI fed motor can be started and run at a constant rotor frequency at maximum torque per ampere. Hence, the constraints on starting torque. Starting current and standstill impedance, as applicable in a conventional supply fed designed motor are irrelevant to the design of a VSI fed motor.

(ii) The VSI fed motor can be accelerated at constant rotor frequency, so starting and run –up of the drive are not affected by parasitic torques. Hence, the selection of stator and rotor slots can now be made based on leakage reactance considerations, while in conventional motor design stator and rotor slots are normally selected so as to minimize parasitic torques.

(iii) The conventional supply fed motor has its rotor design based on a compromise between efficiency and starting torque. But in view of point (i), a low resistance rotor, free from the skin effect, giving higher efficiency is preferred in the case of a VSI fed motor.

(iv) To improve the performance of the motor during high slip acceleration, rotor bars are skewed in a conventional supply fed motor. However, the VSIA fed motor can be operated with controlled rotor frequency, but the rotor skewing is again desirable to obtain a higher values of the leakage reactance to reduce the magnitudes of flux and current corresponding to higher harmonics, so as to get the least torque pulsation.

(v) Although the power factor of the VSI fed motor does not directly affect the power factor of the AC supply system, the power factor of the motor is important as it influences the selection of the inverter components.

As the VSI fed motor suffers from the problems of torque pulsation and additional losses due to the various harmonics present in the inverter output voltage, these motors should have:

(a) A leakage inductance as high as possible to reduce the amplitude of harmonic currents and fluxes, so as to achieve the least torque pulsation and reduce the losses corresponding to the higher harmonic currents and fluxes;

(b) A high value of magnetizing inductance to reduce torque pulsation;

(c) A low rotor resistance to obtain higher efficiency.

3. Formulation of VSI fed squirrel cage induction motor design.

The design optimization of a VSI [4, 9] fed cage motor is formulated as a general non-linear programming problem as follows.

Find $X(x_1, x_2, \ldots\ldots x_n)$, such that

$F(X)$ is optimum

Subject to

$g_f(X) \leq 0 \qquad j = 1, 2, \ldots\ldots m$

and

$x_1 < x_i < x_{Ui} \qquad I = 1, 2, \ldots\ldots, n$

Where all x are independent design variables. F(X) is the objective function to be optimized to make the design optimum either in terms of cost and/or performance. The $g_i(X)$ are the constraints imposed on the design.

3.1 ***Design variables***

A set X of nine independent variables which affects constraints and/or objective functions is listed below:

(1) Stator stack length to pole pitch ratio x_1

(2) Average air gap flux density (T), x_2

(3) Ampere –conductor per metre, x_2

(4) Stator winding current density (A/mm^2), x_4

(5) Rotor winding current density (A/mm^2), x_5

(6) Stator slot depth to width ratio, x_6

(7) Rotor slot depth to width ratio, x_7

(8) Length of air gap (mm), x_8

(9) Stator core depth (mm), x_g

3.2 Imposed constraints

The following constraints are imposed on the design to make it practically feasible and acceptable:

(1) Stator tooth flux density (T) < 2.00
(2) Rotor tooth flux density (T) < 2.00
(3) Maximum torque (p.u) ⩾ 2.10
(4) No- load current (p.u) < 0.30
(5) Torque pulsation over frequency range (p.u) <0.13
(6) Starting current at minimum frequency (p.u) <1.65
(7) No- load power factor at minimum frequency <0.05
(8) Full-load slip < 0.05
(9) Full – load power factor >0.90
(10) Full- load efficiency >0.85
(11) Full- load stator temperature rise <60^0C
(12) Full-load rotor temperature rise <60^0C

3.3 *Objective functions*

To have a practical machine which is acceptable to the customer, four different objective functions are considered while designing the machine:

(1) Cost of active materials (manufacturing cost)
(2) Cost of annual energy consumed
(3) Cost of annual energy consumed plus 20% of active material cost (for interest, replacement and depreciation);
(4) Torque pulsations.

The cost of active material is the first objective function. This was computed considering the costs of the conducting material and the magnetic material separately. The cost of the magnetic material (i.e iron) was taken as N260 per kg; the cost of copper as the conducting material was taken to N600 per kg.

The 'cost of annual energy consumed' is the second objective function. It was computed taking 2500 annual operating hours of the motor and the rate of energy consumption as N11.37 per kWh. This objective function is considered from the viewpoint of the duty cycle of the machine

A mixed objective function (20% of active material cost plus cost of annual energy consumed) is the third objective function and is important to consider from the viewpoint of the growing cost of energy as well as the cost of manufacturing the motor. The design of the motor using this objective function is cost as well as efficiency guard the interest of both customer and manufacturer, so that the resulting design will be marketable.

The fourth objective function is the 'torque pulsation' (see the Appendix for its calculation). The torque pulsation as an objective function is essentially considered to make the drive stable, hence the operating speeds where it is very high and the performance of the drive in terms of speed range deteriorates. Hence, this objective function will safeguard the interest of users in terms of speed range, which starts from12Hz and goes up to 60Hz.

4. Optimization technique

The design optimization of the VSI fed cage induction motor is a higher non-linear, multivariable constrained optimization problem. It may be solved using either direct or indirect search methods. Here, an indirect search method, the sequential unconstrained minimization technique (SUMT), in conjunction with Rosenbrock's method of rotating coordinates is used.

4.1 **SUMT**

In the SUMT [10] the constrained optimization problem is converted into a series of unconstrained problems in the following manner.

Let us take the beginning of the kth iteration.

$$P(X, r_k \ \sum_{j=1}^{m}\{(\frac{1}{G_j\ (X)}\} \qquad \text{eqn (1)}$$

where $P(X, r_k)$ is known as the augmented objective function. The second term on the right-hand side of eqn(1) is called the penalty term and it is used to ensure feasibility during the minimization process. The scalar r_k (>0) is called the penalty factor. Gj (X) is normalized for all the constraints g_j (X) such that $-1< G_j(X) < 0$. The optimization process is started with a set opt X_0 of n variables. That is, an initial feasible design satisfying all the constraints. The starting value of r_k is so selected that $P(X, r_k)$ is twice F(X), then, the augmented function $P(X, r_k)$ is minimized with the help of a suitable unconstrained minimization technique (in the present paper Rosenbrock's method is used), without any constraint to get a point, say X_k. now, the new augmented function $P(X, r_{k+1})$ is formed with $r_{k+1}<r_k = cr_k$, where $0< c <1$), and again minimized with X_{k+1}. In this process of unconstrained minimization of $P(X, r_k)$ for a decreasing sequence of values of r_k, it is necessary to used a proper convergence criterion to identify the optimum point. The convergence criterion may be that the process is continued for either a predetermined number of iterations or until the progress in the objective function F(X) becomes less than a specified small quantity. The value of c was taken equal to ¼ .

4.2 ***Rosenbrock's method***

The method of rotating coordinates, given by Rosenbrock [11], can be considered as a further development of Hook and Jeeve's method [10]. Earlier this method was employed [12, 13] in many applications. Here this method is used in conjunction with the SUMT. In this case the coordinate system is rotated in each stage of minimization in such a manner that the first axis is oriented towards the locally estimated direction of the valley and all the axes are made mutually orthogonal and normal to the first one.

5. **Results and discussion**

The developed computer program is applied to optimize the design of the VSI fed cage induction motor with the following specifications: 7.5 kW, 400V, four-pole. Delta-connected cage motor; there are 48 stator slots and 36 rotor slots' the stators slots are semi closed and rectangular in shape. The optimized design results are given in Table 1 and each design is for a particular objective function. Assuming the normal design as the base design, the following salient features of the optimized design may be noted from the tabulated result.

*TABLE 1**: Optimum design results for the7.5kW, 60V, 4-pole, delta connected VSI fed squirrel cage induction motor***

Item Variables	Normal design	F(X)=A	F(X)=B	F(X)=C	F(X)=D

Stack length to pitch ratio	1.10	1.0044	1.266	1.2016	0.7996
Average air-gap flux density(T)	0.45	0.4915	0.4309	0.4545	0.4717
Ampere-conductor/m (A/m)	24000	25126.19	25419.32	26236.17	24070.26
Stator current density(A/mm^2)	6.00	6.4174	4.00	4.892	5.1336
Rotor current density(A/mm^2)	8.00	7.8927	5.00	5.00	5.00
Depth of stator core (mm)	30.0	26.317	34.53	25.50	35.955
Length of air-gap (mm)	0.45	0.3500	0.3500	0.3500	0.371
Stator slot depth to width ratio	4.00	3.0417	3.912	2.7001	2.758
Rotor slot depth to width ratio	3.50	3.99997	3.9999	4.0000	4.000
Constraint					
Max stator tooth flux density (T)	1,12	1.38	1.24	1.57	1.41
Max rotor tooth flux density(T)	1.475	1.632	1.81	1.961	1.74
Max torque (p.u)	2.12	2.10	2.15	2.24	2.10
No-load current(p.u)	0.2564	0.2417	0.2205	0.2654	0.2253
Torque pulsation over freq. range(p.u)	0.11985	0.1135	0.1225	0.1218	0.1052
starting current at min. freq.(.u)	1.616	1.619	1.4749	1.600	1.503
No- load PF at min freq.	0.0365	0.0406	0.0463	0.0375	0.4243
Full- load slip	0.0497	0.0474	0.0298	0.0296	0.0291
Full-load PF	0.950	0.9096	0.9104	0.9001	0.9114
Full-load efficiency(%)	86.56	85.68	89.46	88.53	88.46
Full-load stator temp rise(^{0}C)	43.80	51.51	33.20	43.69	36.15
Full-load rotor rise(^{0}C)	51.49	52.94	31.27	32.79	27.46
Objective functions					
A. active material cost(N)	1976.9	1656.5	2503.5	1948.7	2087.4
B. operating cost(N)	5200.4	5216.1	5016.1 *	126556.3	126593.4
C. mixed obj. funct (20%A+B)(N)	5695.8	5547.6	5516.8	5452.0*	5481.2
D. torque pulsation(p.u)	0.11986	0.1135	0.1225	0.1218	0.1052*
Improvement in objective function	16.21%	3.54%	2.57%	12.22%	
Main dimensions					
Stator bore diameter(m)	0.164	0.161.43	0.1555	0.1539	0.179
Stack length(m)	0.1414	0.1273	0.1546	0.1451	0.1124
Stator outer diameter(m)	0.2799	0.26385	0.2903	0.2575	0.3045
Equivalent circuit parameters					
Stator resistance per phase(Ω)	2.619	2.791	1.775	2.164	2.364
Rotor resistance phase(Ω)	2.473	2.361	1.5739	1.5417	1.5062
Stator reactance per phase(Ω)	1.196	4.821	5.487	4.781	5.23
Rotor reactance per phase(Ω)	1.401	5.991	6.5152	6.145	6.413
Magnetizing reactance (Ω)	176.53	188.02	219.59	177.43	210.56
Core loss resistance(Ω)	1268.15	1207.12	1236.46	1222.58	1273.46
Commutating capacitance(μF)	1.6500	1.6500	1.6500	1.6500	1.6500
Commutating inductance(mH)	4.100	4.100	4.100	4.100	4.100
Commutation time of inverter Circuit (ms)	1.90	1.90	1.90	1.90	1.90
No. of functions computed	7372	5222	6516	8187	

(a) When the optimization is attempted for active material cost as the objective function, the resulting design (active material cost reduced by 16.21% and operating cost only increased by 0.31%) comes out to the advantage of the manufacturer. With the increasing cost of electrical energy the interest of the consumer can only be safeguarded if the operating cost is also given due consideration while forming the objective function. Therefore, if optimization is done on the basis of operating cost only, the manufacturing cost rises(active material cost increased by 26.63% and operating cost reduced by 3.54%). Hence to make the design favorable for both manufacturer as well as customer, a design with a mixed objective function gives a reduced active material cost (by 1.43%) and a reduced operating cost (by 2.66%). The overall cost using the mixed objective function is reduced by 2.57%

(b) The torque pulsation for the stability of the drive is considered as a performance based objective function. With torque pulsation as an objective function, the manufacturing cost rises, while the operating cost is reduced. But for VSI fed operation of the cage motor, the torque pulsation is of major importance as compared with the manufacturing cost of the machine. The optimized value of the torque pulsation over the whole operating frequency range, that is. 12 to 60Hz , turns out to be 0.1052 p.u., the active material cost is increased by 5.59% and the operating cost is reduced by 2.63%

(c) To keep the torque pulsation within the acceptable range, the magnetizing inductance should be as high as possible. In the present.

Investigation, the magnetizing inductance is increased by 19.28%

(d) To have the least torque pulsation, the magnitude of the higher order harmonic currents, hence fluxes should be as low as possible. This means that the same harmonic reactance should be as high as possible. If the torque pulsation is considered as an objective function, the trends of the design variables, constraints and machine parameters as well as the machine dimensions are as follows:

(i) The stack length to pole pitch ratio decreases, the ampere-conductor/m increases and the stator and rotor current densities decreases. The air-gap length is the highest among all the optimized designs and the depth of the stator core is greater. The stator slots become deeper.

(ii) The machine has more leakage reactance approximately four times more than the normally designed machine because leakage reactance's corresponding to the predominant fifth and seventh harmonics are much larger than the fundamental reactance. With these higher values of harmonic reactance the torque pulsations as well as losses due to higher harmonic currents and fluxes are suppressed considerably. The magnetizing reactance is greater and the stator and rotor winding resistances are lower. The magnetizing reactance is greater and the stator and rotor resistances are lower. The stator bore diameter is larger and the core length is smaller.

(e) One major advantage is the VSI fed machine is that an inverter circuit can be selected in which each pair of thyristors is not commutated individually but the inverter is commutated as a whole, which permits excessive stored energy in the commutating elements to free-wheel in the local circuit without involving the machine winding. Hence, unlike its counterpart, the current source inverter (CSI), there is no overshooting of capacitor voltage. Hence, unlike its counterpart, overshooting of capacitor voltage. Hence unlike the CSI, the VSI system is free from voltage spikes. But at the same time the VSI system suffers from the disadvantage that with the above-mentioned inverter circuit the highest possible frequency is less than that of the CSI system, due to the commutation of the VSI as a whole at every commutation of the thyristor pairs. Hence, the drive suitable for VSI fed operation should have a low value of torque pulsation. The torque pulsation is reduced by modifying the machine parameters so that their magnetizing reactance and their leakage reactances are as high as possible

6. Conclusions

The work in this investigation was motivated to achieve a modified design of the squirrel cage induction motor suitable for voltage source inverter fed operation. It is concluded that the modified design should have larger reactances, a greater diameter, a smaller stack length, and a larger magnetizing impedance to reduce the torque pulsations.

Hence, based on the present investigation, it is concluded that the most suitable design of the cage motor for VSI fed operation is the design with torque pulsation as and objective with the highest possible values of magnetizing reactance and leakage reactance. In the present work a step by step method using SUMT in conjunction with Rosenbrock’s method is used to obtain and optimum design. Thus, the resulting design, when the motor is fed from a VSI, gives a satisfactory performance

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