ISTANBUL UNIVERSITY –
JOURNAL OF ELECTRICAL & ELECTRONICS ENGINEERING

YEAR : 2009 (969-975)
VOLUME : 9
NUMBER : 2

A SURVEY ON DESIGN OPTIMIZATION STUDIES OF INDUCTION MOTORS DURING THE LAST DECADE

F. KENTLİ

Department of Electrical Education, Faculty of Technical Education, Marmara University, Göztepe, Istanbul, Turkey

E-mail: fkentli@marmara.edu.tr

ABSTRACT

Optimization methods are widely used in design of electromagnetic devices throughout the years. Moreover, there are many literature surveys on application of optimization methods to electromagnetic devices. This study is focused on optimization techniques in design optimization of induction motors to help researchers to gain background knowledge of most recent studies. In this paper, firstly, induction motor types and optimization methods are introduced. Secondly, brief explanations on each application of optimization methods are given in chronological order and according to induction motor types. Lastly, these studies are classified and evaluated.

Keywords: *Design Optimization, Induction Motor*

1. BACKGROUND INFORMATION

This section has two parts. At the first part, background information on induction motor (IM) types are given to describe the problems in literature precisely. The focus in this study is on induction motors because of their prominent use and necessity to narrow the area of study. At the second part, optimization methods used are shortly explained. All optimization methods are not taken into consideration likewise motor types to narrow the area of study.

1.1. Information on induction motor types studied

Induction motors (IMs) are common forms of AC motors. They are called IMs because currents flowing in their rotors are induced by alternating currents. The induced rotor current then produces a magnetic field, which is attracted by the field generated in the stator. Because of the continuously reversing poles of AC power, the stator field rotates and drags or pulls the rotor into a spinning motion. Fig. 1 shows a schematic representation of an IM. When the voltage rises and falls in the stator, a current is induced into the rotor. The induced rotor field acts against the field in the stator and rotary motion is produced. There are two principal types of IM in point of getting the rotating field and construction: single-phase and poly-phase (Fig. 2). IMs take place in Fig. 2 are the rotating types [1],[2],[3],[4]. As known, the linear induction motors are the respective counterparts of rotating induction motors [4].

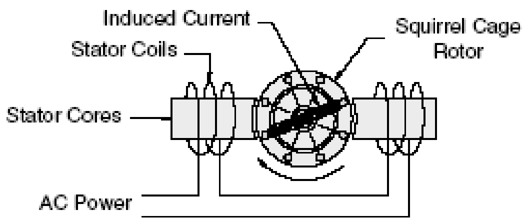

Figure 1. Stylized induction motor schematic[1].

Received Date: 04.09.2009
Accepted Date: 05.11.2009

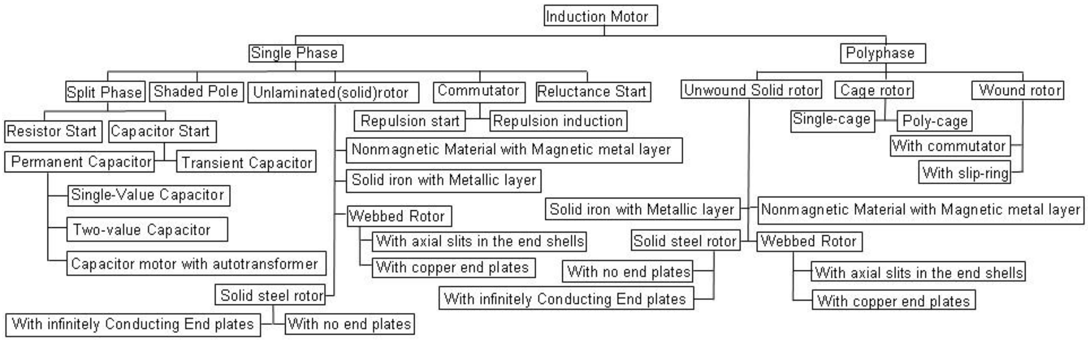

Figure 2. Classification of single-phase induction motors [1],[2],[3],[4].

1.1.1. Single-Phase Induction Motors

Single-phase IMs require additional components and special methods for starting, so they are further classified according to starting method and construction: 1) split-phase IM, 2) shaded-pole IM, 3) unlaminated (solid) IM, 4) reluctance-start IM and 5) commutator IM. The three types of split-phase IMs are resistor - start (RS), transient capacitor - start (TCS), permanent capacitor-start (PCS). PCS IMs are single value capacitor motor, two value capacitor motor (one- capacitor run) and capacitor motor with autotransformer. Commutator IMs are repulsion-start IM and repulsion-IM. IMs with unlaminated (solid) rotor are named according to rotor construction. These are IM with solid steel rotor, solid iron rotor with metallic layer, webbed rotor, nonmagnetic material rotor with magnetic metal layer. Split-phase, shaded-pole and reluctance-start IMs are of the single phase squirrel-cage IM type. Also, commutator-type IMs are of the wound-rotor type. More information can be found in [1],[2],[3],[4].

1.1.2. Polyphase Induction Motors

Polyphase IMs are the most widely used integral - horsepower AC motors because they are simple, ruggedly built, and offer good operating characteristics. Polyphase IMs are classified as unwound (solid)-rotor, (squirrel) cage-rotor and wound-rotor. The former consists of a non- magnetic core which carries a layer of special magnetic material or an unwound cylinder of magnetically hard chrome or cobalt based alloy steel or iron. As seen in Fig. 2, the classification of the polyphase IM with unwound (solid) or unlaminated rotor is the same as that of the single-phase IM with unwound (solid) or unlaminated rotor. The second one contains conducting bars short circuited at the end and embedded within it. The last one consists of a multiphase winding similar to that used for the stator, but electrically short-circuited. More information can be found in [1],[2],[3],[4].

1.2. Information on optimization methods used

A simple optimization problem can be formulated as in Eqn (1).

$$\text{Min } f(\mathbf{x}) \quad \text{subject to}$$
$$g_j(\mathbf{x}) \geq 0 \;\; j=1,2,...,m \text{ and } h_k(\mathbf{x})=0 \;\; k=1,2,...,p \qquad (1)$$

where **x** is n-dimensional design variable vector, $f(\mathbf{x})$ is objective function, $g_j(\mathbf{x})$ are inequality constraints and $h_k(\mathbf{x})$ are equality constraints [5]. Optimization problems differ according to type of each element (Objective, Constraint and Design Variable) of the problem setup and are classified under different categories.

Single or Multiobjective Optimization: If the problem setup has more than one objective, it is called Multiobjective Optimization Problem. Otherwise, it is called Single-objective Optimization Problem. For optimization of induction machines, typical objective functions are efficiency and motor weight (Cost of active materials (cam) and global cost (cam + cost of manufacturing and selling + loss capitalized cost + maintenance cost))

Constrained or Unconstrained Optimization: If the problem setup has any constraint, it is called Constrained Optimization; otherwise, it is called Unconstrained Optimization. A typical design variable set for optimization of induction motors are the number of conductors per stator slot, stator wire gauge, stator core (stack) length, stator bore diameter, stator outer diameter, stator slot height, air gap length, rotor slot height, rotor slot width, rotor cage end – ring width.

Discrete, Integer, Continuous or Mixed Optimization Problem: Optimization problems are named as the type of the variable (discrete, integer, continuous or mixed of them). The number of design variables may be increased or reduced depending on the number of adopted constraint functions. Typical constraint functions are starting/rated current, starting/rated torque, breakdown/rated torque, rated power factor, rated stator temperature, stator slot filling factor, rated stator current density, rated rotor current density, stator and rotor tooth flux density, stator and rotor back iron flux density. Some sample applications can be found in [6].

2. STUDIES ON THE LAST DECADE

2.1. Studies related with single-phase induction motors

Mohammed et.al. [7] presented the design problem of a permanent capacitor-start single-phase induction motor (SPIM) as a nonlinear multi-criterion optimization problem. Weighting min-max method is used to reach the objectives: cost of active material and efficiency or full load of slip and efficiency. Liu et.al. [8] adapted an advanced mathematical method, the filled function method (FFM), to seek the global minimum of the two capacitor-run SPIM considering cost of effective materials. Locke et.al. [9] gave a brief overview of the current methods of power factor correction, and demonstrated a method for selecting the optimal size capacitor for almost any motor. They formulated the problem as a single variable optimization problem with the user free to select variables such as payback period, utility rates, and motor load factor. Cost function is optimized by using graphical and analytical derivation.

Zhou et.al. [10] presented a method to optimize the design of a shaded-pole IM for maximum starting torque with the aid of finite element modeling and a modified hybrid global-local search method, combining the Niching Genetic Algorithm with a direct search method (Modified Hooke-Jeeves). 2D multi-slice finite element model is adopted to calculate the shaded-pole IM's performance. Aluzri et.al. [11] considered the design problem of a shaded-pole IM as a multi-criteria optimization problem and solved by using a nonlinear programming technique. The requirements are represented by weighted elements of objective function vector and a set of constraints. The adopted approach provides the flexibility for the designer to represent the importance of goals in "weights" and find the optimal design according to these weights. Implementation of this approach is presented by designing a motor with two objective functions (starting torque and cost of active materials).

Sarac et.al. [12] applied the GA method on the shaded-pole IM, aiming towards an improvement of its operational and performance characteristics in their study. As an object of investigations the single phase shaded-pole IM is considered to optimize its efficiency. Liuzzi et.al. [13] dealt with the optimization problem of single phase squirrel-cage IM design. They investigated the use of a multi-objective optimization method (Controlled Random Search) to minimize manufacturing cost, starting current and maximize rated efficiency, power factor. Bhuvaneswari et.al. [14] presented a radial basis function (RBF) model for optimal design of SPIM. Simulated Annealing (SA) is used for arriving at the optimal designs concerning maximum efficiency and then RBF network is trained with this optimal data. Developed model is compared with SA, GA and conventional method. Then they [15] presented a comparative study of the various soft computing techniques and their applications to the optimum design of SPIM. The process of optimization has been carried out by using SA, RBF networks, and evolutionary programming. Maximum efficiency is taken as the objective. Later they [16] employed particle swarm optimization (PSO) technique for optimum design of SPIM on the basis of maximizing the efficiency of the motor. They applied their approach to two sample motors and the results are compared with the evolutionary programming (EP) results.

Wang et.al. [17] showed how finite-element analysis and topology optimization of a SPIM of a rotary compressor can be used to reduce the oil circulation rate to the minimum safe level. Shim et.al. [18] aimed to present a 3D multi-objective approach regarding both magnetic and thermal characteristics associated with design of IMs. The adjoint variable topology sensitivity equations are derived using the continuum method for 3D optimization. The proposed method was applied to a SPIM. Commerical Optimization software DOT was used by considering energy and temperature objectives.

2.2. Studies related with three-phase induction motors

Faiz et.al. [19] presented a design procedure of a three-phase squirrel-cage IM for electric vehicles. The objective function is a weighted summation of the motor losses and the motor volume. The objective function is then augmented with the design constraints. The modified Hooke-Jeeves search technique is adapted to solve this constrained nonlinear optimization problem. The influence of the "copper weight/iron weight" ratio on the motor design is studied and the optimum ratio is chosen in order to improve the performance of the motor. Feyzi et.al. [20] used a combination of finite element method (to evaluate performance) and an iteration method, based on conjugate directions to minimize capitalized cost per year. An algorithm for the optimization of the three-phase squirrel-cage IM design is proposed which combined the least square data fitting with golden section method and Fletcher conjugate. Sharitian et.al.

[21] considered multi-objective design optimization of three-phase squirrel-cage IM and reduced it to a new objective function that can be optimized simply by using FE (to solve the motor model) and a simple weighted optimization method. The objective function (capitalized cost of motor) and constraints are replaced with approximations by means of least squares data fitting. Minimization is then performed every iteration on the approximated penalty function until convergence is achieved. Combination of a golden-section and a local quadratic fitting technique is used. For subsequent iterations, conjugated directions are formed according to Polak-Riblere recursion formula. Then they [22] applied three optimization methods, including random, direct search and indirect search methods, enhanced with finite element method (to solve the model) on the design of slots shapes of a three-phase squirrel-cage IM. The motor capitalized cost per year is taken as an objective.

Rao et.al. [23] presented a design optimization problem of a six-stepped inverter fed three-phase squirrel-cage IM for minimum cost and maximum frequency operation. Nonlinear Programming Technique (NPT) employing Powell's unconstrained optimization method together with Zangwill's exterior penalty function formulation is applied to a mathematical model of an inverter fed three-phase squirrel cage IM. Pugsley et.al. [24] sought to posit a new procedure to optimize the geometry of a three-phase squirrel-cage IM for hybrid vehicles (HV). A limited number of finite element computations were used to establish a non-linear electromagnetic model of the machine. This model was then adapted to study the sensitivity of the design for the most significant geometric variations. Commerical Optimization software Pro@DESIGN is used to minimize the cost or mass. Lachecinski et.al. [25] presented a new hybrid optimization algorithm, using genetic and modified deterministic Rosenbrock's algorithm in designing big power three-phase squirrel-cage IM. Min. material and operating unit costs ratio to the price of 1 kWh are taken as objectives. Faiz et.al. [26] used the Hooke-Jeeves search routine to optimize the design of three-phase squirrel-cage IMs for three objective functions, namely efficiency, efficiency-cost and cost. Three optimally designed motors are then compared with an industrial (conventional) motor. Then they [27] designed an optimal three-phase squirrel-cage IM for an electric vehicle by using a modified-Hooke–Jeeves optimization technique and maximum efficiency. The optimal designs are analyzed and compared with varying pole number, rated base speed and slot shapes. Hamid et.al. [28] presented the application of PSO for losses and operating cost minimization control in the three-phase squirrel-cage IM drives. They proposed a strategy for IM speed control considering maximum efficiency. Then, they [29] used two strategies based on PSO and aimed Maximum Efficiency and Minimum Operating Cost. Abdin et.al. [30] presented an artificial neural network based as a predictor for optimum flux for an indirect vector-controlled three phase squirrel cage IM drive in their study. The load torque and speed are used as inputs for the neural network. The optimum flux-producing current is taken as the neural network output. Çunkaş et.al. [31] presented an optimal design method to optimize three-phase squirrel cage IM in manufacturing process. The Genetic Algorithm is used for optimization and three objective functions namely torque, efficiency, and cost are considered. Subramanian et.al. [32] presented a novel multi-objective optimal design of three phase IM using simulated annealing (SA) technique for minimizing annual material cost and annual loss cost as two objectives. The problem is solved by giving weights which reflect the priority of objective functions. They [33] considered three different objective functions (Efficiency or starting torque and full load torque or temperature rise) in designing three-phase squirrel-cage IMs. The simulated annealing algorithm with local search and pattern search is used to obtain an optimum design.

Bellarmine et.al. [34] presented an application of Radial Basis Function Network (RBFN) model for Optimum Design of IM (ODIM). The method utilizes Simulated Annealing (SA) technique to provide optimum design of three-phase IM as training data to the RBFN. Maximum efficiency is taken as objective. Results of RBFN are compared with results of SA and Modified Hooke-Jeeves methods. Liuzzi et.al. [35] concerned the design optimization problem of three-phase IMs as a mixed variable programming problem and proposed a new algorithm (Mixed Integer Variable Algorithm Model). They compared the proposed method with a derivative free method. Minimization of manufacturing cost in euros and maximization of rated efficiency are taken as objectives. Padma et.al. [36] presented a comparative study of the various soft computing techniques and their application to optimum design of three-phase IM design. To maximize the efficiency, design of the IM has to be chosen appropriately. They applied computational intelligence techniques such as artificial neural network, fuzzy logic, genetic algorithm, differential evolution, evolutionary programming, particle swarm optimization, simulated annealing approach, radial basis function, and hybrid approach to solve the IM design optimization problem. These methods are tested on two sample motors and the results are compared and validated against the conventional Modified Hooke-Jeeves design results. Cho et.al. [37] proposed a multi-criteria optimal design of a squirrel-cage IM for an electric vehicle using a niching method using adopting restricted competition selection and compared with niching method using sharing and DC. They used a grading system likewise fuzzy membership to handle the objectives which are efficiency at continuous rated output; efficiency at peak output; power factor at peak output; stator winding temperature rise at continuous rated output; stator winding temperature rise at duty cycle operation; material cost of active part. Jianzhong et.al. [38] investigated the improvements on intelligent simulated annealing (ISA) algorithm. They found that ISA can circumscribe whereabouts the global optimum is by using fuzzy inference method. They applied to the optimal design of pole changing three-phase IMs used in locomotive. The objective function is the cost of the motor which consists of costs of copper conductor and core.

Besnerais et.al. [39] described first a fast analytical model of a variable-speed induction machine which calculates both motor performances and sound power level of electromagnetic origin. This model is then coupled to Nondominating Sorting Genetic Algorithm (NSGA-II) in order to perform global constrained optimizations with respect to several objectives (e.g., noise level, efficiency and material cost). As three-phase squirrel-cage IM design involves both continuous and discrete variables, a modified NSGA-II algorithm handling mixed variables is detailed. They considered two noise objective functions simultaneously: maximum noise level encountered during traction phase, and average noise level. Two other objective functions are studied: material cost and efficiency, the latter being maximized by minimizing. These two objectives are only evaluated at nominal speed.

Çunkaş et.al. [40] presented an optimal design method to optimize total cost (manufacturing + material) of three-phase submersible motors. The genetic algorithm (GA) is used for cost optimization, and a software algorithm has been developed. The 2-D finite element method (FEM) is then used to confirm the validity of the optimal design. Sayyah et.al. [41] applied a genetic algorithm to minimize the total harmonic current distortion (THCD) in three-phase IMs fed by high power inverters, based on an approximate model. Rouabah et.al. [42] investigated an artificial intelligent approach based on genetic algorithms (GAs) for IM efficiency optimization. The efficiency improvement strategy consists of adjusting the magnetizing current component with respect to the torque current component in order to minimize the total copper and iron losses of the machine. Koechli et.al. [43] presented the application of Range and Filter and SQP methods to the design of IMs driving hydraulic pumps on commercial aircrafts. Minimization of weight is taken as objective function. FEM is used to modify the resulted motor. Isfahani et.al. [44] presented a multi-objective optimization method to improve both efficiency and power factor, simultaneously for three-phase single-sided linear IMs. They used an analytical model of the machine to calculate the efficiency and power factor. Then motor parameters and dimensions were optimized by using a genetic algorithm in an appropriate objective function. FEM was used to verify the results and then they [45] used 2-D and 3-D time-stepping finite-element methods to evaluate the analytical results.

3. RESULTS AND EVALUATION

IMs are one of the mostly used electric motors in industry. So, every improvement in design process is important. In this study, it is aimed to show to the researchers the new study areas to improve design processes of IMs and to give recommendations for future studies.

As a conclusion, most of the studies on design optimization of IMs are done on polyphase IMs as shown in Fig. 3. It is three times of the works on single phase. Efficiency and cost are mainly used objectives as seen in Fig. 3. Researchers could study on other objectives (minimizing temperature, starting torque, vibration etc.). Nontraditional optimization techniques (GA, SA etc.) are used more often than gradient based search techniques (Hooke-Jeeves, SQP etc.) (Fig. 3). But, there is still no work on using Ant colony, Bees and Memetic algorithms. GA is mostly used as a nontraditional technique while Hooke-Jeeves technique is mostly used as a gradient based search technique. Moreover, it is seen that FEM is used to help optimization process. As known, most problems can be solved without using FEM. But, on the last decade, the solution without using FEM hasn't been come across throughout former studies.

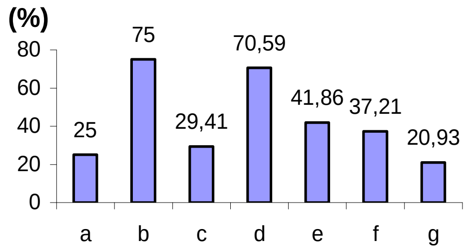

Figure 3. Percentage of studies (a),(b) from perspective of phase number (a- single phase, b- poly phase), (c),(d) according to used optimization technique (c- gradient based, d- nontraditional), (e),(f),(g) according to objective type (e- efficiency, f- cost, g- other).

There is still need to work on multi-objective design optimization of IMs. Higher percentage of the studies is done for polyphase squirrel-cage IMs. There is less work on some motor types (shaded pole, three-phase linear, single-value permanent capacitor, two-value permanent capacitor) and there is no work on other motor types (e.g. wound-rotor) as seen in Fig. 4. It is recommended to study these areas.

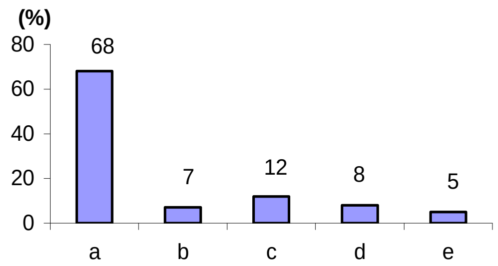

Figure 4. Percentage of studies according to related motor type (a) three-phase squirrel cage, (b) three-phase linear, (c) shaded pole, (d) two-value permanent capacitor, (e) single-value permanent capacitor.

4. REFERENCES

[1] Rizzoni, G., *Principles and Applications of Electrical Engineering*, McGraw-Hill, 2003.
[2] Rosenblatt, J., Friedman, M.H., *Direct and Alternating Current Machinery*, Charles E. Merrill Publishing Co. A Bell & Howell Company, 2nd Edition, Columbus, Ohio, 487-525, 1984.
[3] Say, M.G., *Alternating Current Machines*, Longman Scientific & Technical, Fifth Edition, Singapore, 533-591, 1988.
[4] Sambath, H.P., "Induction Machines with Unlaminated Rotors", Ph.D. Thesis, Department of Electrical Engineering and Electronics, UMIST, Manchester, 1977.
[5] Rao, S.S., *Engineering Optimization: Theory and Practice*, John Wiley & Sons, 1996.
[6] Boldea, I., Nasar, S.A., *The Induction Machine Handbook*, CRC Press, 2001.
[7] Mohammed, I.A., Aluzri, A.M., "Multicriterion optimisation approach in the design of a PCS motor", *IEE Proceedings on Electric Power Applications*, Vol. 147, pp. 87 – 92, 2000.
[8] Liu, X., Xu, W., "A Global Optimization Approach for Electrical Machine Designs", *IEEE Power Engineering Society General Meeting*, pp. 1–8, 2007.
[9] Locke, C., "Optimal capacitor sizing for induction motors", *Canadian Conference on Electrical and Computer Engineering*, Vol. 2, pp. 1162 – 1166, 2000.
[10] Zhou, D., Rajanathan, C.B., Sapeluk, A.T., Ozveren, C.S., "Finite-element-aided design optimization of a shaded-pole induction motor for maximum starting torque", *IEEE Transactions on Magnetics*, Vol. 36, pp. 3551-3554, 2000.
[11] Aluzri, A.M., Mohammed, I.A., "Vector optimization design of a shaded-pole induction motor", *IEEE Transactions on Energy Conversion*, Vol. 17, pp. 374 – 379, 2002.
[12] Sarac, V., Petkovska, L., Cundev, M., Cvetkovski, G., "Comparison Between Two Target Functions for Optimization of Single Phase Shaded Pole Motor Using Method of Genetic Algorithms", *Journal of Materials Processing Technology*, Vol. 161, pp. 89-95, 2005.
[13] Liuzzi, G., Lucidi, S., Parasiliti, F., Villani, M., "Multiobjective optimization techniques for the design of induction motors", *IEEE Transactions on Magnetics*, Vol. 39, pp. 1261 – 1264, 2003.
[14] Bhuvaneswari, R., Subramanian, S., "Optimization of Single-phase Induction Motor Design using Radial Basis Function Network", *IEEE INDICON 2005*, IC170, pp. 35- 40, 2005.
[15] Subramanian, S., Bhuvaneswari, R., "Comparison of Modern Optimization Techniques with Applications to Single-Phase Induction Motor Design", *Electric Power Components and Systems*, Vol. 34, pp. 497-507, 2006.
[16] Subramanian, S., Bhuvaneswari, R., "Optimal design of single-phase induction motor using particle swarm optimization", *COMPEL*, Vol. 26, pp. 418-430, 2007.
[17] Wang, S., Kang, J., Noh, J., "Topology optimization of a single-phase induction motor for rotary compressor", *IEEE Transactions on Magnetics*, Vol. 40, pp. 1591 – 1596, 2004.
[18] Shim, H., Moon, H., Wang, S., "3D topology optimization of magneto-thermal systems", *COMPEL*, Vol. 25, pp. 572 – 580, 2006.
[19] Faiz, J., Ghaneei, M., Keyhani, A., Proca, A.B., "Optimum Design of Induction Motors for Electric Vehicles", *Electric Power Components and Systems*, Vol. 28, pp. 1177 – 1194, 2000.
[20] Feyzi, M.R., Kalankesh, H.V., "Optimization of induction motor design by using the finite element method", *Canadian Conference on Electrical and Computer Engineering*, Vol. 2, pp. 845 – 850, 2001.
[21] Sharifian, M.B.B., Kalankesh, H.V., Feyzi, M.R., "Multi-objective optimization of induction motor slot design using finite element method", *Proceedings of the 10th IEEE International Conference on Electronics, Circuits and Systems*, Vol. 3, pp. 1308-1311, 2003.
[22] Feyzi, M.R., Kalankesh, H.V., Sharifian, M.B.B., "A comparative study of three optimization methods in FEM design of induction motors", *The 4th International Power Electronics and Motion Control Conference*, Vol. 1, pp. 305-309, 2004.
[23] Rao, K.S.R., Ramamoorty, M., "Design optimization of inverter fed 3-phase squirrel cage induction motor", *Proceedings of the Conference on Convergent Technologies for Asia-Pacific Region*, Vol. 4, pp. 1303- 1307, 2003.
[24] Pugsley, G., Chillet, C., Fonseca, A., "Cost - performance - size optimization for automotive induction machines: A fast and accurate FEM, analytical model and optimization mixed procedure", *COMPEL*, Vol. 25, pp. 297-308, 2006.
[25] Lachecinski, S., Dems, M., Wiak, S., "Hybrid optimization algorithms in designing of induction motor at occurrence continuous and discontinuous decision variables", *International Aegean Conference*

on Electrical Machines and Power Electronics, pp. 541 - 546, 2007.
[26] Faiz, J., Sharifian, M.B.B., "Optimal design of three phase induction motors and their comparison with a typical industrial motor", *Computers and Electrical Engineering*, Vol. 27, pp. 133-144, 2001.
[27] Faiz, J., Sharifian, M.B.B., "Optimal design of an induction motor for an electric vehicle", *European Transactions on Electrical Power*, Vol. 16, pp. 15-33, 2006.
[28] Hamid, R.H.A., Amin, A.M.A., Ahmed, R.S., El-Gammal, A.A.A., "New Technique for Maximum Efficiency of Induction Motors Based on Particle Swarm Optmization (PSO)", *32nd Annual Conference on IEEE Industrial Electronics*, Vol. 3, pp. 2176 - 2181, 2006.
[29] Hamid, R.H.A., Amin, A.M.A., Ahmed, R.S., El-Gammal, A.A.A., "New Technique for Maximum Efficiency and Minimum Operating Cost of Induction Motors Based on Particle Swarm Optmization (PSO)", *32nd Annual Conference on IEEE Industrial Electronics*, pp. 1029-1034, 2006.
[30] Abdin, E.S., Ghoneem, G.A., Diab, H.M.M., Deraz, S.A., "Efficiency Optimization of a Vector Controlled Induction Motor Drive Using an Artificial Neural Network", *Proceeding of the 29th Annual Conference of the IEEE Industrial Electronics Society*, Vol. 3, pp. 2543- 2548, 2003
[31] Çunkaş, M., Akkaya, R., "Design Optimization of Induction Motor by Genetic Algorithm and Comparison with Existing Motor", *Mathematical and Computational Applications (MCA)*, Vol. 11, pp. 193-204, 2006.
[32] Subramanian, S., Bhuvaneswari, R., "Multiobjective optimal design of three-phase induction motor using simulated annealing technique", *COMPEL*, Vol. 24, pp. 1415-1427, 2005.
[33] Bhuvaneswari, R., Subramanian, S., "Optimization of Three-Phase Induction Motor Design Using Simulated Annealing Algorithm", *Electric Power Components and Systems*, Vol. 33, pp. 947-956, 2005.
[34] Bellarmine, G.T., Bhuvaneswari, R., Subramanian, S., "Radial Basis Function Network Based Design Optimization of Induction Motor", *Proceedings of the IEEE on SoutheastCon*, pp. 75 – 80, 2005.
[35] Liuzzi, G., Lucidi, S., Piccialli, V., Villani, M., "Design of induction motors using a mixed-variable approach", *Computational Management Science*, Vol. 2, pp. 213-228, 2005.
[36] Padma, S., Bhuvaneswari, R., Subramanian, S., "Application of soft computing techniques to induction motor design", *COMPEL*, Vol. 26, pp. 1324-1345, 2007
[37] Cho, D.-H., Jung, H.-K., Lee, C.-G., "Induction motor design for electric vehicle using a niching genetic algorithm", *IEEE Transactions on Industry Applications*, Vol. 37, pp. 994 – 999, 2001.
[38] Jianzhong, S., Fengxian, B., Renyuan, T., "Optimization design of special induction motors using improved intelligent simulated annealing algorithm", *Proceedings of the Fifth International Conference on Electrical Machines and Systems*, Vol. 2, pp. 1163 - 1165, 2001.
[39] Besnerais, J.L., Lanfranchi, V., Hecquet, M., Brochet, P., "Multiobjective Optimization of Induction Machines Including Mixed Variables and Noise Minimization", *IEEE Transactions on Magnetics*, Vol. 44, pp. 1102-1105, 2008.
[40] Çunkaş, M., Akkaya, R., Bilgin, O., "Cost optimization of submersible motors using a genetic algorithm and a finite element method", *The International Journal of Advanced Manufacturing Technology*, Vol. 33, pp. 223-232, 2007.
[41] Sayyah, A., Aflaki, M., Rezazade, A.R., "GA - based optimization of total harmonic current distortion and suppression of chosen harmonics in induction motors", *International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, pp. 1361 - 1366, 2006.
[42] Rouabah, Z., Zidani, F., Abdelhadi, B., "Efficiency Optimization of Induction Motor Drive Using Genetic Algorithms", *Proceedings of the 4th IET Conference on Power Electronics, Machines and Drives*, pp. 204-208, 2008.
[43] Koechli, C., Fussell, B.K., Prina, S.R., James, D.A., Perriard, Y., "Design optimization of induction motors for aerospace applications", *IEEE Industry Applications Conference*, Vol. 4, pp. 2501-2505, 2004.
[44] Isfahani, A.H., Lesani, H., Ebrahimi, B.M., "Design Optimization of Linear Induction Motor for Improved Efficiency and Power Factor", *IEEE International Electric Machines & Drives Conference*, pp. 988-991, 2007.
[45] Isfahani, A.H., Ebrahimi, B.M., Lesani, H., "Design Optimization of a Low-Speed Single-Sided Linear Induction Motor for Improved Efficiency and Power Factor", *IEEE Transactions on Magnetics*, Vol. 44, pp. 266 – 272, 2008.

Fevzi Kentli was born in Isparta, Turkey in 1950. He received the B.Sc., M.Sc. and Ph.D. degrees in Electrical Edu. and Eng. from Ankara Technical Teacher's Training College, Bosphorus Uni., Istanbul Technical Uni. and Marmara University, Turkey, in 1973, 1979, 1981 and 1992, respectively. In 1974, he joined the Electrical Dept. of Ankara Tech. Teacher's Training College as a Research Ass. He was promoted to Instructor and Lecturer in 1981, Ass. Prof. in 1993. From 1981 to 1993, he worked at the Elec. Dept. of Ankara Tech. Teacher's Training College, Istanbul Tech. Teacher's Training College and Tech. Edu. Fac. of Marmara Uni. as an Instructor and a Lecturer. Since 1993, he is working at the Elec. Edu. Dept. of Tech. Edu. Fac.of Marmara Uni. as an Ass. Prof. His research interests are in the areas of electrical machines and their controls and design.