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Loss Minimization in an Induction Motor Driven by a Voltage-Source-Inverter

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Abstract: Energy saving via loss minimization in an induction motor has been known for years. The concept is sometimes introduced separately from the drive mechanism. Conventionally, most of the methods utilize approximated machine models; some assume known parameters that are difficult to measure or estimate. This article describes power loss minimization in small induction motors driven by voltage-source inverters. It is shown that numerical computing is the effective approach to obtain optimum excitation voltage and frequency subject to load torque variation such that losses are minimized. The method employs the motor parametric model with accurately known parameters, i.e. resistances and inductances of the stator and the rotor, respectively. The article describes an easy-to-conduct experiment to capture the motor speed-torque characteristics that in turn are used for parameter identification via genetic algorithms. The proposed method of loss minimization is useful under variable load torque conditions. Its usefulness and limitation are discussed with experimental results shown.

Keywords : power loss minimization, induction motor, genetic algorithm, energy saving

Introduction

Small three-phase induction motors have been widely used in industries for several decades. Their drive technology utilizes various types of inverters. The drive most commonly found employs voltage-source inverters (VSI) to achieve the constant v/f, the fixed-v/variable-f, and the variable-v/variable-f schemes, respectively. Such drives can produce controlled characteristics that are useful for industrial applications. Additionally, the inverter is considered as an efficient means to save energy in the electrical drive. However, more energy savings are still possible with power loss minimization incorporated into the drive control scheme.

Loss minimization of electric drives may follow two main routes: (1) loss minimization for some predefined speed profiles, and (2) loss minimization at every steady-state speed and torque required. The former is dominant in railway and traction applications. The latter, that is the main interest of this paper, is useful for a variety of industries. Under the assumptions of constant motor parameters, and equal stator and rotor frequencies, the exciting frequency to minimize losses in ac machines can be found. The method is effective in a narrow region of operation where the slip is around 1. Furthermore, the motor parameters change with frequencies leading to some errors in derived expressions for loss minimization thereof. Significant energy savings could be achieved providing motor parameters are accurately known. This method is very limited because the required parameters are difficult to measure or estimate. At light load, significant energy savings are possible via field-oriented control. The insertion of an external impedance to improve the power factor of the rotor circuit is effective for wound-rotor induction motors at the expense of the I^2R loss. In addition, this approach causes harmonics into the system, and care must be taken to guarantee satisfactory transient response. Modification of the constant v/f inverters commercially available to attain the minimum loss operating point is possible via perturbing rotor frequency. The scheme requires no knowledge of motor parameters and is suitable for nonlinear loads such as fans and pumps. Minimizing loss in induction motors via optimum input voltage and frequency when saturation, skin effect, and source harmonics are taken into account is also possible. However, these factors are very difficult to measure or predict in practice. The major work in this area utilizes flux control to minimize losses. Artificial intelligence techniques have been applied to identify optimum flux as well as to control flux and magnetizing current for loss minimization. The d-q loss model has been proposed for loss minimization in various types of dc and ac motors.

It is the central idea of the present work that the factors rendering loss minimization must be easily controlled. Since the work is proposed for the VSI induction motor drive, to control the excitation voltage and frequency is therefore the main task. Regarding the loss minimization objective, the motor parameters, i.e. resistances and inductances of the stator and the rotor, of the steady-state model must be accurately known. We propose that these parameters be identified from the actual speed-torque characteristics obtained from simple experiments. We apply the genetic algorithm (GA) to identify the parameters that appear to be nonlinear functions of the excitation voltages. The terms representing the core losses can be obtained from the no-load and the blocked-rotor tests. With our proposed loss expression, it is possible to calculate the optimum excitation voltage and frequency that minimizes losses at all times corresponding to the load torque variation and speed demand. In terms of implementation of the loss minimization controller, one may consider either real-time and on-line calculation or a viewable table approach to search for the optimum excitation. The choice depends on the performance of the hardware used.

This paper is organized into four sections, including the introduction. In the materials and methods section, we have included an explanation on the motor equivalent circuit, identification of its parameters, a review of the genetic algorithm (GA), loss expressions and an approach to loss minimization. The experimental results, advantage, and limitations of the proposed method are also discussed can be found under the section on results and discussion. The last section provides our conclusions.

Materials and Methods

Motor equivalent circuit and parameters

Most portions of motor losses arise during steady-state operation. Thus, an equivalent circuit of the motor plays an important role in loss minimization. For a small three-phase induction motor, the electrical model shown in Figure 1 is widely accepted. The shunt branch appears at the input terminals because its impedance is large compared to the stator impedance. Referring to Figure 1, s is slip, while R_i and L_i are motor parameters. These parameters are assumed constant conventionally and obtained from the no-load and the blocked-rotor tests. Realistically, only the core loss term represented by R_c and L_m may assume constant values. R_c=3.3114 kΩ, and L_m=0.5098 H are obtained from the conventional tests for our slip-ring induction motor of 4 poles, 1500 rpm synchronous speed, 1.5 hp, 380 V_{rms}, 50 Hz ratings. The other parameters vary according to excitation voltage and frequency, temperature, saturation characteristics, harmonics and skin effect. From the practical viewpoint, it is more convenient to consider the parameters as the function of excitation voltages while the other effects are lumped within. Our assumption is acceptable because the motor's parameters are based on the true speed-torque characteristics. The resulting nonlinear functions representing the parameters lead to a fine treatment of loss minimization.

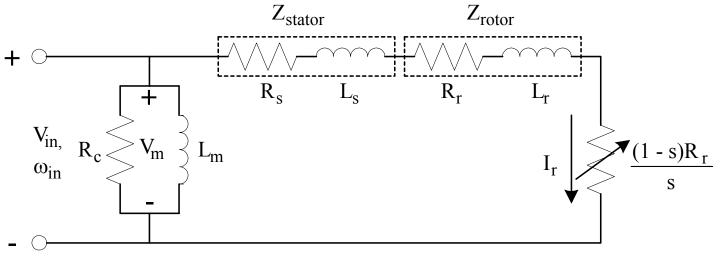


Figure 1. Equivalent circuit of an induction motor.

To obtain accurate parameters requires observations of the true motor characteristics and offline identification. Figure 2 depicts the equipment set-up for monitoring the motor speed-torque curves. This work utilizes GA for identification and it is reviewed herewith. The proposed method leads to simpler modelling and identification, as well as the easy addition of an energy saving controller for the motor.

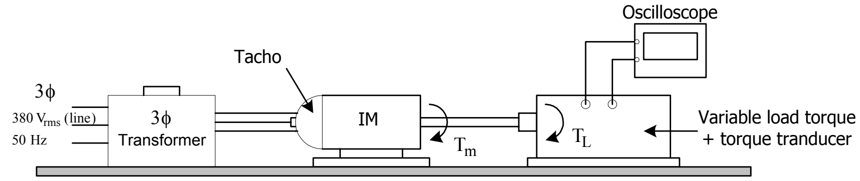


Figure 2. Experimental set up for observations of motor speed-torque characteristics.

Genetic algorithm (GA)

GA is one of the efficient search methods based on the principle of natural selection. It has been successfully used as a tool for optimization problems in broad fields such as engineering, economics, etc. GA can provide approximate solutions for multivariable optimization problems. It has also been applied successfully to identify the parameters of induction motors. To apply GA appropriately, the problem must firstly be converted to a criterion function called “fitness function”. This function represents the performance of the system. The higher the fitness value, the better the performance. GA consists of three main procedures, namely; selection, genetic operation and replacement, respectively. Generally, at the first step, GA starts a random selection of population from the population set. Then the fitness evaluation is invoked. The retained population must pass the minimum requirement of the fitness evaluation while the rest is discarded. These retained members are then parented to produce offspring. All the parents and offspring have to go through the process of fitness evaluation again and only the strong ones are retained. These strong members are then used as replacements to the startup population. Following this, parenting reoccurs and the process is repeated until the fittest member or optimum solution is found. More detailed information regarding GA may be found in the literature. A brief summary of the construction of GA is as follows:

1) *Define chromosome:* For an optimization problem, the parameters to be searched have to be defined as parameter strings. These strings can be coded as binary or real and are called chromosomes.
2) *Define the fitness function:* The fitness function is the performance index of GA used to resolve for acceptable solutions. The design of the fitness function can be based on the problem's requirement, e.g. error, convergent rate, etc.
3) *Generate initial population:* The initial population of N sets are generated randomly with the size of N chosen arbitrarily.
4) *Generate next generation or stop:* To generate the next generation, GA uses the operations of reproduction, crossover and mutation. A stop criterion must be defined such as a number of repetitive loops, acceptable error, etc.

Identification

To obtain the parameters of the equivalent circuit requires true motor characteristics. Some experiments were conducted on the test bed depicted in Figure 2 to capture the motor speed-torque characteristics. Line-to-line voltages of various rms values are fed to the motor and the speed-torque characteristics recorded. Some of the test results are illustrated in Figure 3 where the voltage values are line-to-line. The jagged curves shown in Figure 3 represent the observed motor characteristics. The smooth curves are obtained from calculations based on the equivalent circuit model. In GA terms, the motor's parameters R_s, R_r, L_s, and L_r are defined as chromosomes. In order to have an efficient GA search, some initial assumed solutions and search boundaries fed into the searching routine are particularly useful. The results obtained from the conventional tests of the motor are suitable for initial assumed solutions with search boundaries given. The conventional tests yield $R_s = 6.4333\ \Omega$, $R_r = 4.1178\ \Omega$, and $L_s = L_r = 0.0289$ H.

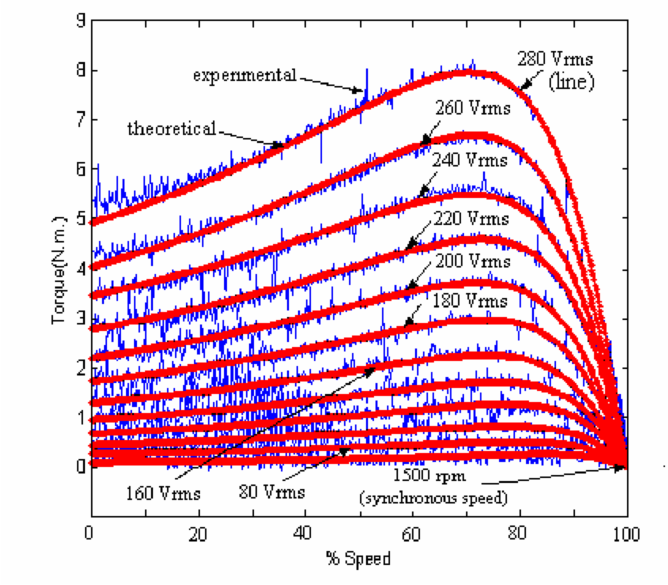


Figure 3. Motor characteristics.

The search boundaries are R_s: 7-15 Ω, R_r: 4.5-7.5 Ω, L_s and L_r = 0.0239-0.0446 H, respectively. Resolution of the search for each parameter is 30 bits. These parameters are concatenated to form a single chromosome of 120-bit resolution. After random selection of the initial population, they are converted to real values and subjected to the fitness test.

The fitness function is given by

$$\text{Fitness function} = \frac{1}{\varepsilon} \tag{1}$$

where

$$\varepsilon = \frac{\sum_{i=1}^{N} e(i)}{N} \tag{2}$$

The error term e(i) is defined by $[\hat{T}(i) - T_a(i)]^2$. T_a is the actual torque obtained from measurement. $\hat{T}$ is the estimated torque expressed by

$$\hat{T} = \frac{V^2}{\omega_s} \frac{\hat{R}_r / s}{(\hat{R}_s + \hat{R}_r / s)^2 + (\hat{X}_s + \hat{X}_r)^2} \tag{3}$$

where $\hat{X}_s = 2\pi f L_s$, $\hat{X}_r = 2\pi f L_r$, and any symbols with ^ representing estimated values. At each trial of the search, the torque is estimated according to the equation (3), and the error calculated. The closer the value of the estimated torque to the actual torque, the higher the fitness value. The search stops at 3,000 counts. The error convergence is monitored through the searching process. One example showing the convergence of error to zero during the search is depicted in Figure 4.

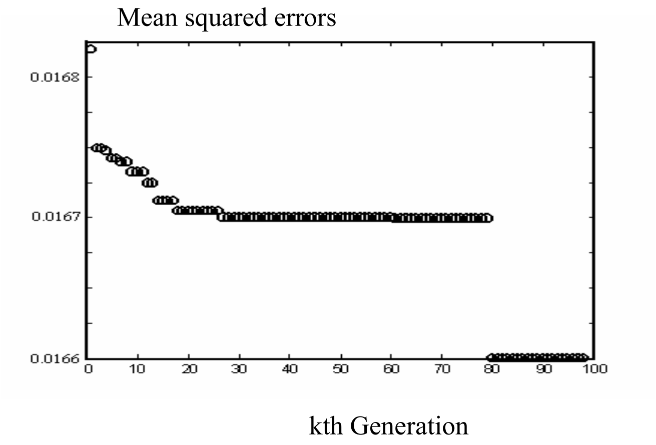
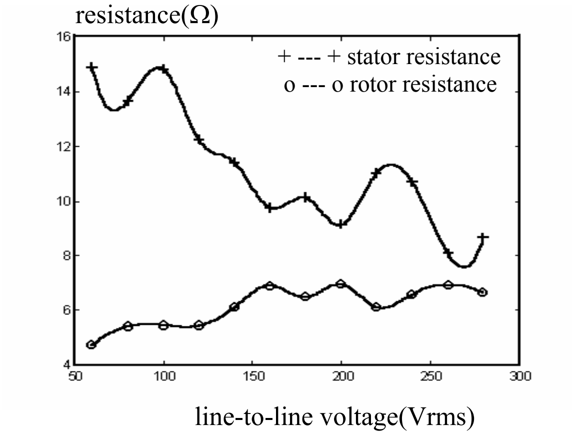


Figure 4. Convergence of estimation error during the search by GA. This case is for the 160 Vrms line input Voltage.

Figure 5 illustrates the estimated motor parameters composed of stator and rotor resistances and inductances, respectively. Figure 5(a) depicts the stator and rotor resistances, while the inductances are depicted in Figure 5(b). Table 1 gives the details of corresponding numerical data. The data exhibit nonlinear relationships to the exciting line voltages, that are, in this work, represented by the cubic spline approximation.

(a)



(b)

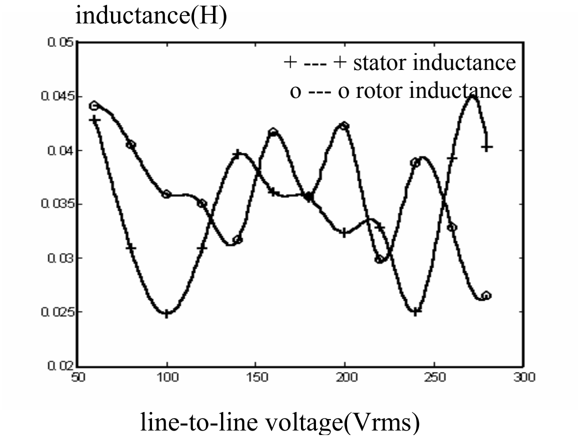


Figure 5. Identified motor parameters (a) resistances, (b) inductances.

Table 1. Numerical data resulting from GA identification for various voltages.

line-to-line voltage(Vrms)	$R_s(\Omega)$	$R_r(\Omega)$	L_s(H)	L_r(H)
60	14.8863	4.7375	0.0428	0.0441
100	14.8182	5.4533	0.0248	0.0359
140	11.4050	6.1207	0.0396	0.0317
180	10.1102	6.4891	0.0356	0.0357
220	11.0193	6.1219	0.0328	0.0298
280	8.6603	6.6382	0.0402	0.0265

Loss expression and approach to minimization

In electrical machinery, stator, rotor, and core losses dominate the overall power losses. Stray, friction and windage losses exist, however they are small enough to be considered negligible. When drive is brought into play, converter losses exist and can be lumped into stator loss. In this case, the total power losses of the motor can be expressed as

$$P_{\text{loss, total}} = \text{stator copper loss+rotor copper loss+core losses.}$$

Equation (4) describes the power losses mathematically

$$P_{loss,\ total} = |I_s|^2 R_s + |I_r|^2 R_r + \frac{|V_m|^2}{R_c}$$

$$= V^2 \left[\left| \frac{Z_2 + Z_m}{Z_T} \right|^2 R_s + \left| \frac{Z_m}{Z_T} \right|^2 R_r + \left| \frac{Z_2 Z_m}{Z_T} \right|^2 / R_c \right] \qquad (4)$$

where

$$Z_1 = R_s + j2\pi f L_s \qquad (5)$$

$$Z_2 = \frac{R_r}{s} + j2\pi f L_r \qquad (6)$$

$$Z_m = \frac{R_c j2\pi f L_m}{R_c + j2\pi f L_m} \qquad (7)$$

$$Z_T = Z_1 Z_2 + Z_1 Z_m + Z_2 Z_m \qquad (8), \text{ and}$$

$$\text{slip } s = \frac{N_s - N_m}{N_s} \qquad (9)$$

Descriptions of these parameters are in the nomenclature. The resistances and inductances of the stator and the rotor, respectively, in the above relations can be substituted by numeric values resulting from cubic spline interpolation. Furthermore, the torque of an induction motor can be expressed by

$$T = \frac{P_{ag}}{\omega_s} = V^2 \left| \frac{Z_m}{Z_T} \right|^2 \frac{R_r}{s} \cdot \frac{1}{\omega_s} \qquad (10)$$

From the equations (4) and (10), one can realize that

$$P_{loss,\ total} = T \cdot \omega_s \cdot \frac{s}{R_r} \left[\left| \frac{Z_2 + Z_m}{Z_m} \right|^2 R_s + R_r + \frac{|Z_2|^2}{R_c} \right] \qquad (11)$$

Equation (11) is a useful model for implementing loss minimization in an induction motor. It shows that the total power losses depend on load torque, synchronous speed, motor speed, exciting voltage and frequency. The analysis is simple, yet the loss model can cope with the machine's nonlinear characteristics via the accurately identified parameters.

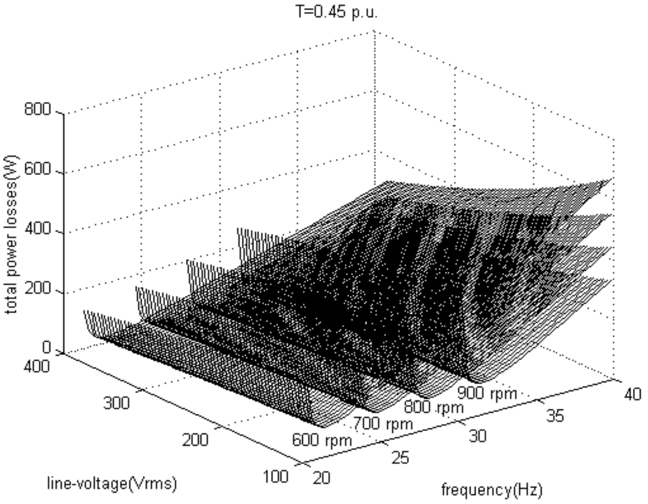


Figure 6. Surface plot of the total power losses in an induction motor driven by a VSI as a function of speed, exciting voltages, frequencies, and constant load torque at 0.45 p.u.

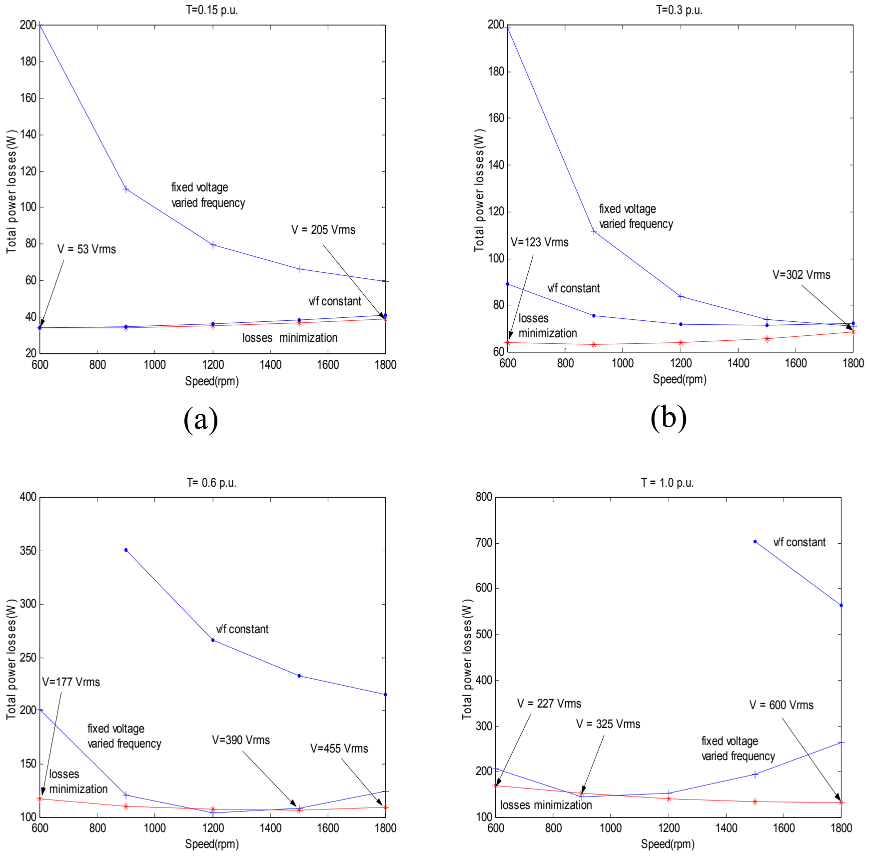
With suitable substitution of the impedances in the equation (11), one can compute the power losses accurately. As an example of the results, Figure 6 illustrates the surface plot of the losses. Sliding surfaces can be noticed as the speed varies. The illustration shows clearly that some particular frequencies yield minimum power loss lines. These frequencies can be computed accordingly. This computing approach is more attractive than conventional differentiation to find the minimum point because the conventional method results in a very high order polynomial. In practice, reduced order via some approximation is unavoidable. This could eventually introduce a considerable amount of errors to practical results.

Results and Discussion

Referring to Figure 6, the surface plot of the total power losses reveals the possibility of minimum loss attainment. This figure is of the case 0.45 p.u. load torque. Similarity in the shape of these surfaces can be assumed for different loads. The rpm values indicated in the figure represent the steady-state speed demanded. The surface slides upward in accordance with the increase in speed. The amount of total power losses also varies due to changes in line-to-line voltage (rms) excitation. Still, minimum loss line can be found for each case at a specific exciting frequency.

Referring to the equation (11), the load torque T is known from measurement or estimation, the motor resistances and inductances are obtained from identification and the synchronous speed is also known. In terms of implementation, real-time computing based on this equation to obtain optimal exciting voltage and frequency is possible. The optimal excitation will result in minimum power loss according to individual speed command. Offline calculation with a viewable table approach is also an alternative. The real-time computing approach requires a high performance processor for implementation. The viewable table approach needs only a low-cost processing unit with somewhat more complicated programming. The solution of optimal excitation can be used to instruct some switching devices to drive the motor. Furthermore, the proposed method of loss minimization can be viewed as the adaptive algorithm of an energy saving controller for the ac drive.

Simulation has become a tool to assess the usefulness and limitations of the proposed method. Simulation runs were conducted for varied load (0-50 % full-load) and speed (600-1800 rpm). Figure 7 illustrates the simulation results that provide a comparison of three drive schemes in terms of total power losses. These schemes are v/f constant, fixed voltage with varied frequency and the proposed method, respectively. The ratings of the motor under test are 380 Vrms, 1.5 hp, 50 Hz, 4 poles, and 1500 rpm synchronous speed. Referring to Figure 7, the voltage parameters shown therein are line-to-line. Figures 7(a) and (b) show that the proposed method is the most efficient approach to minimize losses in induction motors with light load, e.g. 0.15 and 0.3 p.u., respectively. When the load torque is up to about half the manufacturers rating, the proposed method is still efficient as can be seen from Figure 7(c) in which the torque is 0.6 p.u. With high load torque (above half rated), the proposed method is not attractive because the amount of energy saved is not significant and excessive voltage must be applied to the motor. The stress caused by the excessive voltage can damage the motor insulation. Nonetheless, the proposed method is still efficient in a low speed range as can be observed from the results shown in Figure 7(d).



(a) (b)

(c) (d)

Figure 7. Calculation results compare the total power losses that occurred in the various drive schemes namely loss minimization, constant v/f, and fixed-V-varied-f. (a) load torque = 0.15 p.u., (b) load torque = 0.3 p.u., (c) load torque = 0.6 p.u., and (d) load torque = 1.0 p.u.

Figure 8 shows the diagram representing our hardware implementation. The IGBT modules are main switching devices. The proposed method has been implemented as control software together with suitable data tables. The PC executes the control algorithm coded in C. It reads the speed and load torque from sensors through a 12-bit A/D converter. The numerical results obtained from the control algorithm are switching commands in turn sent to two micro-controllers through eight logical outputs. These microcontrollers perform real-time switching functions to drive the chopper and the inverter, respectively.

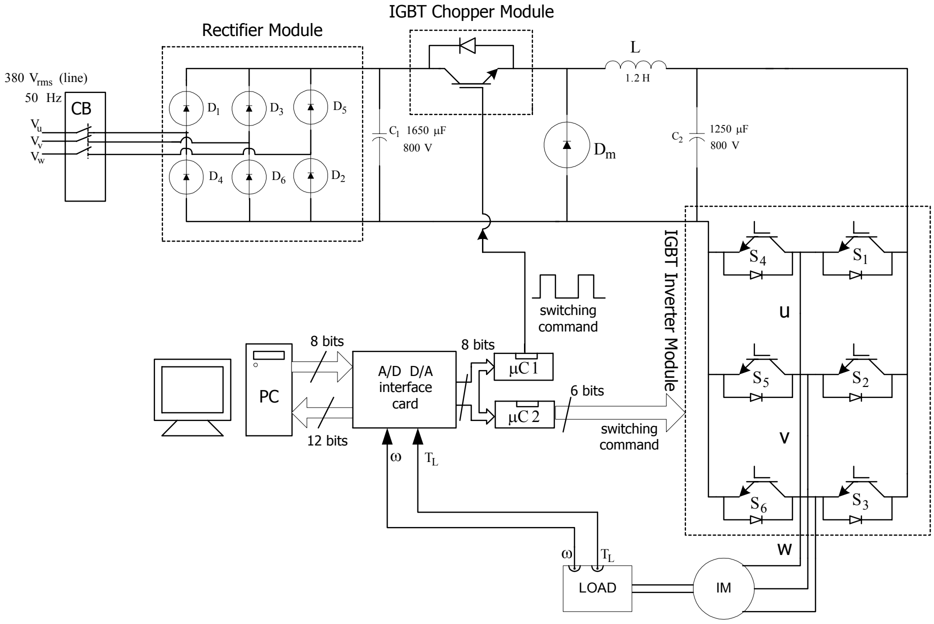


Figure 8. Hardware implementation.

Tables 2 and 3 give details of the experimental results in which the values of the input power (P_{in}) and the power factor (p.f.) were measured at the input terminals of the motor by using FLUKE^{TM} 41B.

Table 2. Experimental results of the system without the energy saving controller.

Load (%)	**Speed (rpm)**	**P_{in} (W)**	**p.f.**	**line-to-line voltage (Vrms)**	**f(Hz)**
0	1500	145	0.25	380	50
10	1497	200	0.32	374.12	50
20	1487	280	0.44	365.12	50
30	1475	380	0.55	357.50	50
40	1462	490	0.66	348.49	50
50	1450	600	0.72	339.14	50

Table 3. Experimental results of the system with the controller.

Load (%)	**Speed (rpm)**	**P_{in} (W)**	**p.f.**	**line-to-line voltage (Vrms)**	**f(Hz)**
0	1500	56	0.87	81.41	55.5
10	1500	125	0.80	162.81	52.2
20	1500	245	0.82	208.19	52.1
30	1500	370	0.83	242.14	51.7
40	1500	480	0.82	274.01	51.1
50	1500	590	0.81	305.19	50.5

Table 4. Experimental results of the system with the controller for a constant speed (1800 rpm) drive.

Load (%)	**Speed (rpm)**	**P_{in} (W)**	**p.f.**	**line-to-line voltage (Vrms)**	**f(Hz)**
0	1800	66	0.83	103.92	65.3
10	1800	155	0.82	173.97	63.1
20	1800	290	0.80	240.41	62.4
30	1800	430	0.83	269.16	62.7
40	1800	590	0.83	306.92	62.6
50	1800	720	0.83	333.59	62.6

Referring to Table 2, for the case of the motor driven as rated without the controller, the motor speed and the terminal voltage drop naturally when the load increases. The input power increases according to the load increase. The motor power factor is very low at light load. Even at about half the rated load, the power factors are still considerably low. For the case of the implemented system represented by the diagram in Figure 8, to maintain a constant speed at various loads is possible with the proposed controller. However, the experimental results shown in Table 3 reflect the actual input power fed to the motor under the same condition of speed and load as for the case of the motor running without the controller. This is for comparison purposes of the input power and the power factor. The two right-hand columns of Table 3 show the optimum excitation line-to-line voltage and frequency corresponding to the load. It is noticeable that the proposed method is very effective for 0-30% load in terms of input power savings. The amount of energy saving ranges from 3-60% approximately. Above 40% load, the amount of energy saving is not significant. In terms of power factor at the motor terminals, the proposed method significantly yields a power factor around 0.8 or better, for the whole load range. Additionally, the data in Table 4 gives the general idea of driving the motor at a constant speed, i.e. 1800 rpm, with the proposed controller. The power factor at the motor terminals is maintained around 0.8. For all cases, the power factor at the utility interface is around 0.9. The simulation and experimental results agree and confirm the effectiveness of our proposed loss minimization method.

Conclusion

This article presents a new approach to power loss minimization in small induction motors driven by voltage-source-inverters. The proposed method employs motor equivalent circuit, i.e. motor parametric model. The model's parameters can be accurately identified from true motor characteristics. Experiments conducted are simple and require instruments commonly found in electrical machine laboratories. The loss model incorporates the variation of exciting voltage, frequency, and load torque as major factors. Some minor factors, e.g. temperature and harmonic effects, are viewed as being lumped into the loss model. Under this consideration, the representation of motor parameters substantially includes the motor's nonlinear characteristics. Hence, the loss model and the proposed loss minimization method are very accurate and can cope with machine nonlinearity to a certain extent. The computing results show that the proposed method is efficient when the load torque ranges from 0 to half the rating. Above half rated load, the method is attractive for low speed range. Implementation of the method as an adaptive algorithm for energy saving in ac drives is not complicated. The implementation approach can be either real-time computing.

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