A NEW SOFT STARTING METHOD FOR WOUND–ROTOR INDUCTION MOTOR

Mohammad Bagher Bannae Sharifian — Mohammad Reza Feyzi
Mehran Sabahi — Meysam Farrokhifar *

Starting of a three-phase Induction motor using a starter rheostat in rotor circuit has some disadvantages. A new method for starting of a three-phase motor by using a parallel combination of resistors, self-inductors and capacitors in rotor circuit is proposed in this paper. The proposed method ensures the soft and higher starting torque as well as limited starting current as compared to shorted rotor method. The characteristic curves for both methods (shorted rotor and rotor with added elements) are provided. The mathematical model based on the steady-state equivalent circuit of the induction motor is expanded in frequency domain and the required computer program is prepared using an optimization method. The values for added elements to rotor circuit are calculated in such a way that minimum starting time considering current and torque limitations are achieved.

K e y w o r d s: induction motors, starting methods, rotor impedance, starting torque

Nomenclature

V_{LL} – Line to line voltage
f_S – Line frequency
F_R – Rotor current frequency
R_t – Stator resistance
R_2 – Rotor resistance
X_t – Stator reactance
X_t – Rotor reactance
V_t – Input phase voltage
R_a – Starting resistor
X_{ca} – Starting capacitor reactance
X_{La} – Starting inductor reactance
T_d – Induced electrical torque
t_{st} – Motor starting time
ω_l – Steady state angular speed of the rotor
N – Per-unit speed of the rotor
S – Slip
S_m – The slip at maximum torque
S_l – Steady state slip
A_t – Acceleration torque

1 INTRODUCTION

The starting torque which is of great importance in case of driving high-inertia loads is proportional to rotor resistance. Several studies have been done to improve starting properties of an induction motor [1–4]. It is reasonable to have a high resistance during starting period, then to decrease it and finally remove that from rotor circuit when motor reaches to its steady state condition. On the other hand, since during starting period, slip is equal to unity by considering the equivalent circuit of an induction motor, it is clear the input impedance which is seen by supply side, has the lowest value causes to create high current which is drawn by motor during the starting period. Therefore, using the drivers to limit the starting current is recommended [5–7]. Such drivers which provide the above mentioned goals are required in order to improve the performance of the induction motors.

In this paper a new method for soft starting of an induction machine is presented. By using a parallel combination of resistors, self-inductors and capacitors in rotor circuit soft and higher starting torque as well as limited starting current as compared to shorted rotor method are archived, without any external driver requirements.

2 STARTING OF A SQUIRREL CAGE MOTOR

2.1 On-line direct starting

In this method stator is directly connected to the utility. The current drawn by motor, depending on its design class, will be from 5 to 7 times the nominal current rating. Since this amount of current flows only for a short period of time, it would not damage the squirrel cage motor, but it may cause undesirable drop in supply voltage and subsequently affects the performance of other equipment connected to the same supply.

2.2 Starting with a resistor or an inductor in stator circuit

In this method a resistor or reactor is used between supply and motor. In starting instant, some voltage is

* Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran, sharifian@tabrizu.ac.ir, feyzi@tabrizu.ac.ir, sabahi@tabrizu.ac.ir ,me.farrokhifar@gmail.com

DOI: 10.2478/v10187-011-0005-3, ISSN 1335-3632

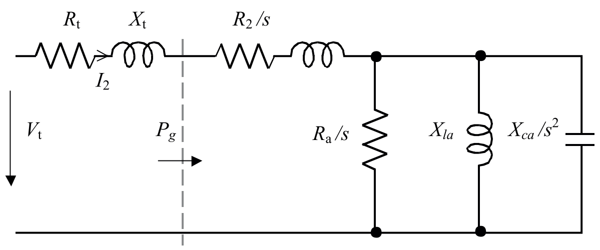

Fig. 1. Equivalent circuit of an induction motor with added elements

dropped across starter resistor or reactor and only a fraction of supply voltage is present across motor terminals, thus the starting current is decreased. As speed of the motor increases, the amount of resistor or reactor is manually decreased and when reaches its nominal speed rating the resistor or reactor is completely shorted out. The disadvantages of this method are the need for extra equipment in order to gradually remove the resistor or reactor from the circuit and low starting torque due to low starting voltage across the motor.

2.3 Autotransformer starting method

In this method, a fraction of supply voltage is applied to stator using an autotransformer. This approach decreases the current drawn by motor and the supplied current. When the motor approaches to its nominal speed, autotransformer is removed from the circuit and entire voltage of the supply is applied to the induction motor. In this method, quite less current is drawn from supply as compared to previous method, but the extra equipment is still required. On the other hand, the starting torque is small as a result of low amount of voltage at starting instant, so this method is not useful for high inertia loads.

2.4 Y–Δ starting method

This method is used for motors that are designed to operate with Δ connection. The phases of stator are initially Y connected using a TPTD switch and when motor reaches its steady state, the stator winding change to Δ connection. In this method the starting voltage across each phase is $\frac{V_{LL}}{\sqrt{3}}$ and thus the starting current is lower which leads to a smaller starting torque. The extra equipment and TPTD switch are also required.

3 STARTING OF WOUND–ROTOR INDUCTION MOTOR

The simplest and most inexpensive method for starting of wound-rotor motor is adding a resistance to rotor circuit and applying the nominal voltage to stator. The added resistance to rotor circuit

a) Decreases the starting current;
b) Increases the starting torque;
c) Improves the starting power factor.

But this method has some disadvantages as follows

a) Mechanical switches and corresponding problems;
b) Discontinuity in starting torque;
c) Sudden changes in supply current

In order to improve the wound-rotor induction motor conditions and overcome the above-mentioned problems, using a parallel combination of resistors, self-inductors and capacitors in rotor circuit is proposed in this paper. The rotor frequency given by $f_r = s\,f_s$ is high at starting instant, therefore, the maximum current flows through capacitor and resistor at starting instant and this increases the starting torque and improves the starting power factor. As the speed of the motor increases, the rotor frequency decreases, thus the impedance of self inductor significantly decreases and effectively shorts the resistor. In this condition, the capacitor acts as an open circuit which leads to an improved operating condition. During starting, the effective rotor resistance, is gradually decreased which ensures the smooth starting of the motor.

4 MOTOR EQUIVALENT CIRCUIT

Since the transient components of the starting current are quickly damped as compared to starting period and considering the fact that starting impact torque on shaft has no effect on the average accelerative torque [1], so using the steady state equivalent circuit is acceptable. Of course, the equivalent circuit is modified according to new method theory. Numerical optimization method is used to calculate the value of added elements in order to achieve minimum starting time considering rotor current and torque limitations. The equivalent circuit of an induction motor is shown in Fig. 1. In this circuit R_t, X_t and V_t are the parameters of the Thevenin's equivalent circuit for stator and R_2 and X_2 are rotor parameters. Other parameters R_a, X_{la} and X_{ca} represent the added resistor, self inductor and capacitor respectively. In this circuit, the impedance of rotor equivalent circuit is $R+jX$ which is calculated as follow

$$R = \frac{X_{ca}^2 X_{la}^2 R_a}{S^5 D}\,, \tag{1}$$

$$X = \frac{\big(X_{la} X_{ca} R_a^2\big)\big(\frac{X_{ca}}{S^2} - X_{la}\big)}{S^4 D}\,, \tag{2}$$

$$D = \frac{\big(X_{la} X_{ca}\big)^2}{S^4} + \Big(\frac{X_{la} R_a}{S} - \frac{X_{ca} R_a}{S^3}\Big)^2, \tag{3}$$

$$I_2 = \frac{V_t}{\sqrt{X_{eq}^2 + R_{eq}^2}} \tag{4}$$

where, $X_{eq} = X_t + X + X_2$ and $R_{eq} = R_t + R + R_2/2$.

In order to determine the air gap and produced torque, the rotor current can be used as follows

$$T_d = 3I_2^2 \frac{\big(R + \frac{R_2}{s}\big)}{\omega_s}\,. \tag{5}$$

5 ESTIMATION OF OPTIMIZED VALUES FOR ELEMENTS

The main object of adding resistor, capacitor and self inductor to rotor circuit is improving the starting performance. Therefore the values of elements should be determined in such a way that the best starting conditions are achieved. One of the important parameters is the starting time, tst, which has to be calculated considering the following conditions

1) The starting current should never exceed the values limited by utility or thermal capabilities of motor.
2) The starting torque should never exceed the limits determined by the type of the load or maximum allowed shaft torque.
3) The motor, with the added elements, should have acceptable operating performance under normal conditions.

By combining the mechanical equation of motor and the attached load, the following relation is derived

$$T_{st} = \int_0^{\omega l} \frac{J}{T_d - T_l} \mathrm{d}\omega \,. \tag{6}$$

The load torque is generally stated as follows

$$T_l = K_1 + K_2\omega^p + K_3\omega^q \,. \tag{7}$$

With proper calculation of the values for K_1, K_2, K_3, p, q it is possible to model almost every type of mechanical loads. In this case, the generated torque is a function of motor parameters as well as the added elements. Thus, for a motor which is coupled to a certain load, the following relation can be derived

$$T_{st} = F\big(R_a, X_{ca}, X_{la}\big) \,. \tag{8}$$

The main requirement is to obtain minimum starting time provided that the following electrical and mechanical constraints are met.

$$I_2 \le K_I I_r \,, \tag{9}$$

$$T_d \le K_T T_r \,. \tag{10}$$

The value of K_T and K_I is determined considering the thermal limitations of motor and supply as well as the type of the load. In order to minimize the t_{st} the integral function of the following relation should have its maximum value

$$\int_0^{\omega l} (T_d - T_l)\mathrm{d}\omega \,. \tag{11}$$

Considering the constraints in relations (9) and (10), the following algorithm is used to solve the optimization problem

1) The value of X_{la} is calculated in such a way that, shorts the added elements under nominal motor speed condition.
2) The value of the integral function is calculated for a wide range of R_a and X_{ca}. This is done by using trapezoidal numerical integration.
3) The values of R_a and X_{ca} are calculated in such a way that the integral function has its maximum value without exceeding of current and torque limitations.
4) The performance of the motor under normal operation conditions with the added elements is evaluated by checking the slip value. If any of these variables is not satisfactory the value of X_{la} is changed and the above mentioned stages are repeated until the desired results are achieved.

6 CASE STUDY

In order to verify the efficiency of the proposed approach, all the above mentioned stages are applied to a typical induction motor and the results are analyzed. The motor specifications stated as pu values are $R_1 = R_2 = 0.015$, $X_1 = X_2 = 0.09$, $X_m = 4$.

The proposed algorithm is evaluated on the motor with added elements in rotor circuit considering the following five conditions

1) The condition without limitation which means there is no limitation including mechanical (generated torque) and electrical (rotor current). It is clear that since no limitation exists for current, the rotor current could increase as much as several times of its normal value.
2) Shorted rotor condition is checked in order to compare the performance of motor in the presence of added elements with normal shorted rotor condition.
3) The condition in which a fixed resistor is added to rotor is also checked to compare the common starting method with the proposed one.
4) The condition of considering electrical limitations on rotor current. In this case those values of R_a, X_{la} and X_{ca} are acceptable in simulation program which satisfy the constraints.
5) The condition of considering mechanical limitations on rotor current. In this case the generated torque can not exceed a certain value. The calculation of R_a, X_{la} and X_{ca} in order to find the minimum starting time should also satisfy the constraints.

The provided software on the basis of the proposed algorithm calculates the values of R_a, X_{la} and X_{ca} to achieve the minimum starting time by considering motor limitations. As mentioned earlier, one of the conditions to accept the calculated values of R_a, X_{la} and X_{ca} is that the slip value should be reasonable under normal operation conditions. If the value of slip is high or load torque curve cuts the generated torque curve in unstable points, the value of X_{la} is modified and the program is run again to achieve acceptable values for R_a and X_{ca}. In this study, the motor is evaluated under three operating conditions including: with no limitation, with current limitation and with generated torque limitation for $0.3 + 0.4N$ and $0.15 + 0.25N + 0.35N^2$ loads, where N represents speed of the rotor. The results of the program

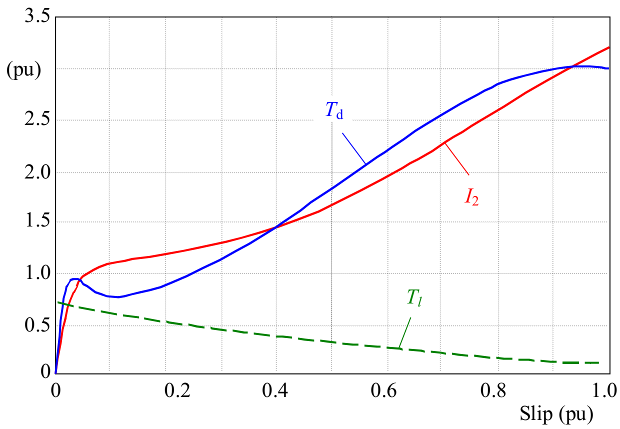

Fig. 2. T_d, T_l and current (I_2) with respect to slip; current restricted status $T_l = 0.15 + 0.25N + 0.35N^2$

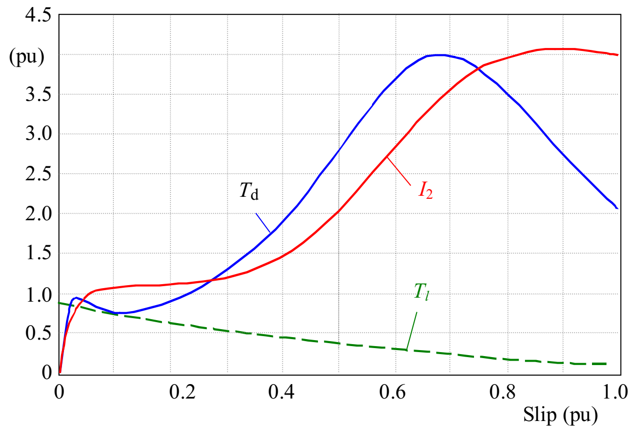

Fig. 3. T_d, T_l and current (I_2) with respect to slip: torque restricted status $T_l = 0.15 + 0.25N + 0.35N^2$

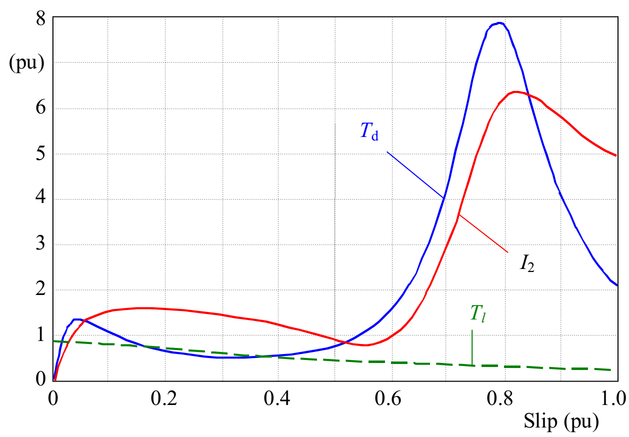

Fig. 4. T_d, T_l and current (I_2) with respect to slip: unconstrained status $T_l = 0.15 + 0.25N + 0.35N^2$

which is derived by using MATLAB software are shown in Tables 1 to 5. Table 1 represents the results in no limitation status. Table 2 shows the analysis results for initial status of motor without adding the elements which is the basis for comparison with added elements condition. Table 3 shows the analysis results when the 0.165 pu resistor is added to rotor circuit. Further advantages of the proposed method are obviously seen by evaluating this table. Table 4 shows the results when the current is limited to 3.15 pu and in Table 5 the results when the torque is limited to 4 pu, are shown. The effects of limiting the current and torque on starting speed and other characteristics of the motor are clearly shown in Tables 4 and 5.

The main goal of optimization is to find suitable values for added elements to achieve minimum starting time. Optimization program calculates the values of added elements and plots the characteristic curves considering the current and torque constraints. The torque and the current curves corresponding to the calculated values of added elements are shown in Figs. 2 to 4 for no limitation status, torque $T_d < 4$ pu and current $I < 3.15$ pu status, shorted rotor status and rotor with added resistor respectively.

The effect of proposed method on the performance of 3-phase wound-rotor induction motors is clearly seen in these figures. As we can see from the figures corresponding to shorted rotor status, when the slip is near 0.5 the current has a constant value which is almost equal to starting current and then begins to fall. In other words, the motor draws a quite high current for a longer period of time as compared to optimized status.

But in the optimized method it is seen that current decreases with a smooth slope immediately after starting. The proposed method has also good effects on starting torque. In order to evaluate this effect, we can compare the curves for shorted rotor status, rotor with added resistor and the curve for optimized method. It is seen that, in shorted rotor status, the starting torque is lower than 0.5 pu.

By adding a constant 0.165 pu resistor the starting torque reaches 2.5 pu while in current-restricted optimization $I < 3.15$ pu the starting torque is about 3.1 pu, therefore the starting torque is also improved. Considering other advantages of the proposed method including stating time optimization and other benefits, this method is very suitable for motor starting. The following results are achieved by considering of figures and tables.

1) The minimum starting time is achieved when there are no limitations (mechanical and electrical). In this case At has its maximum value. It is also notable (as in Table 1) that in case of light loads the accelerating level of A_t is increased.
2) With identical loads the accelerating level of the method in which parallel elements are added is much higher than shorted rotor status (Table 2). This level is also higher than the case a pure resistor is added to achieve maximum starting torque (Table 3).
3) When the rotor current is limited to 3.16 pu which is the same as maximum current with shorted rotor, the accelerating level is significantly decreased (Table 4).

Table 1. The results of optimization with no limitation

T_l (pu)	$0.15 + 0.25N + 0.35N^2$	$0.3 + 0.4N$	0.6	0.08
R_a (pu)	0.36	0.26	0.21	0.6
X_{ca} (pu)	0.055	0.055	0.055	0.076
X_{la} (pu)	0.3	0.3	0.3	1
A_t	1.911	1.8	1.7	2.46
I_m (pu)	4.04	0.04	4.04	3.97
S_m	0.68	0.68	0.684	0.665
S_l	0.015	0.014	0.011	0.001

Table 2. The results of starting with shorted rotor

T_l (pu)	$0.15 + 0.25N + 0.35N^2$	$0.3 + 0.4N$	0.6	0.08
A_t	0.532	0.532	Not start	0.95
I_m (pu)	3.15	3.15	" "	3.15
Sm	0.084	0.084	" "	0.084
T_m (pu)	2.38	2.38	" "	1.38
S_l	0.011	0.011	" "	0.001

Table 3. The results of starting with added resistor to rotor: $R_a = 0.165$

T_l (pu)	$0.15 + 0.25N + 0.35N^2$	$0.3 + 0.4N$	0.06	0.08
A_t	1.05	1.3	1.198	1.68
I_m (pu)	1.15	1.15	1.15	2.15
Sm	1	1	1	1
T_m (pu)	2.52	2.52	2.52	2.52
S_l	0.123	0.126	0.116	0.016

Table 4. Results of optimization with current limitation: $I \leq 3.15$ pu

T_l (pu)	$0.15 + 0.25N + 0.35N^2$	$0.3 + 0.4N$	0.6	0.08
R_a (pu)	0.36	0.11	0.11	0.11
Xc_a (pu)	0.055	0.127	0.13	0.146
X_{la} (pu)	0.3	0.3	0.3	0.4
A_t	1.46	1.35	1.24	1.83
I_m (pu)	3.01	3.01	3.01	3
S_m	0.95	0.95	0.95	0.93
S_l	0.015	0.014	0.011	0.001

Table 5. The results of optimization with torque limitation:T ($T_d \leq 4$ pu)

T_l (pu)	$0.15 + 0.25N + 0.35N^2$	$0.3 + 0.4N$	0.6	0.08
R_a (pu)	0.11	0.11	0.11	0.11
X_{ca} (pu)	0.055	0.055	0.055	0.076
X_{la} (pu)	0.3	0.3	0.3	1
A_t	1.911	1.8	1.7	2.46
I_m (pu)	4.04	4.04	4.04	3.97
S_m	0.68	0.68	0.684	0.665
S_l	0.015	0.014	0.011	0.001

4) When the torque is limited to 4 pu, the accelerating level reaches the value it had in case of limited current method but it is still lower than unlimited method (Table 5).

Considering these points we conclude that minimum starting time is achieved when there are no mechanical and electrical limitations. The starting current in this case is much higher than shorted rotor current but the starting time is very small and power factor is highly improved. The nominal voltage rating of capacitor should tolerate the voltage across its terminals during starting period. In unconstrained status the peak value may reach 2.4 pu.

7 CONCLUSION

In this paper a new approach for soft and quick starting of a 3-phase wound-rotor induction motor was provided. This method requires connection of external impedance including parallel combination of self-inductance, capacitor and resistor. The estimation algorithm for calculation of optimized values of elements, which results in minimum starting time and desired performance, is explained. Topics are as follows:

1) In the proposed method the starting time is much lower than the shorted rotor method or common method in which a resistor added to rotor circuit.
2) In this optimized method the starting torque is much higher than the shorted rotor method or common method in which a resistor added to rotor circuit.
3) The power factor during starting is improved due to capacitor in the circuit. Because of the elimination of resistor the rotor losses is decreased as compared to the common method in which a resistor added to rotor circuit.
4) The minimum starting time is achieved when there are no mechanical and electrical limitations. In case of light loads the starting time is smaller.
5) By applying the current and torque limitations the starting time increases but it is still lower than the shorted rotor method or the common method in which a resistor added to rotor circuit.

References

[1] SAY, M.: Alternating Current Machines, 2nd Edition, Pitman, England, 1984.

[2] BADR, M. A.—ABDEL-HALIM, M. A.—ALOLAH, A. I.: A Nonconventional Method for Fast Starting of Three Phase Wound-Rotor Induction Motors, IEEE Trans. on Energy Conversion **11** No. 4 (1996), 701–707.

[3] ABDEL-HALIM, M. A.: Smooth Starting of Ring Induction Motors, IEE Trans. on Energy Conversion **12** No. 4 (1997), 317–322.

[4] HAMOUDA, R. M.—ALOLAH, A. I.—BADR, M. A.—ABDEL-HALIM, M. A.: A Comparative Study on the Starting Methods of Three Phase Wound-Rotor Induction Motors – part I, IEEE Trans. on Energy Conversion **14** No. 4 (1999), 918–922.

[5] ZENGINOBUZ, G.—CADIRCI, I.—ERMIS, M.—BARLAK, C.: Soft Starting of Large Induction Motors at Constant Current with Minimized Starting Torque Pulsations, IEEE Trans. on Industry Applications **37** No. 5 (2001), 1334–1347.

[6] RASHAD, E. M.—RADWAN, T. S.—RAHMAN, M. A.: Starting and Vector Control of Series-Connected Wound-Rotor Induction Motor in Super Synchronous Mode, IEEE 39th IAS Annual Meeting Conf., Industry Applications, 2004, pp. 32–39.

[7] LI, W.—LU, J.—LIU, M.—ZHAO, J.: Design of Intelligent Soft-Start Controller for Induction Motor, Proceedings of Third Inter. Conf. on Machine Learning and Cybernetics, 2, 2004, pp. 908–912.

Received 22 April 2009

Mohammad Bagher Bannae Sharifian (1965) studied electrical power engineering at the University of Tabriz, Tabriz, Iran. He received the BSc and MSc degrees in 1989 and 1992 respectively from the University of Tabriz. In 1992 he joined the electrical engineering department of the University of Tabriz as a lecturer. He received the PhD degree in electrical engineering from the same university in 2000. In 2000 he rejoined the Electrical Power department of faculty of electrical and computer engineering of the same university as an assistant professor. He is currently professor of the mentioned department. His research interests are in the areas of design, modeling and analysis of electrical machines, transformers, electrical drives, and electric and hybrid electric vehicles.

Mohammad R. Feyzi received his BSc and MSc in 1975 from University of Tabriz in Iran with honors degree. He worked in the same university during 1975 to 1993. He started his PhD work in the University of Adelaide, Australia in 1993. Soon after his graduation, he rejoined to the University of Tabriz. Currently, he is an associate professor in the same university. His research interests are finite element analysis, design and simulation of electrical machines and transformers.

Mehran Sabahi was born in Tabriz, Iran, in 1968. He received the B.Sc. degree in electronic engineering from the University of Tabriz, the M.Sc. degree in electrical engineering from Tehran University, Tehran, Iran, and the Ph.D. degree in electrical engineering from the University of Tabriz, in 1991, 1994, and 2009, respectively. In 2004, he joined the Faculty of electrical and computer engineering, University of Tabriz, where he has been an assistant professor since 2009. His current research interests include power electronic converters and power electronic transformers.

Meysam Farrokhifar was born in Tabriz, Iran, on February 15, 1981. He received the BSc and MSc degrees from University of Tabriz in power electrical engineering in 2004 and 2007 respectively. Currently, he is a member of IEEE industrial electronics society and Iranian national electro technical committee (INEC). He has published more than 15 technical papers. His fields of interest include power system optimization, electrical machines, transformers and Intelligent Methods for Optimization.