PERFORMANCE ANALYSIS OF INVERTER-FED SINGLE-PHASE INDUCTION MOTOR

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ABSTRACT

This study investigates the effects of the presences of harmonics in the exciting voltage when using a dc/ac inverter on the performance of a single-phase induction motor, the investigation includes theoretical and experimental parts and together with performance comparison of the motor with the nominal sinusoidal input voltage. The computed performance of the motor depend on the theoretical equivalent circuits which are modified to take into account the existence of harmonics in the inverter output to compute the performance at each harmonic order. It conclude from the analysis that the pulsating torque is inherent in single-phase induction motor even when supplied from a sinusoidal voltage source. Particular attention has been devoted to the pulsating torque when the motor is supplied from an inverter and the most important pulsations have been identified. The comparisons of simulation and measured results show good correlation between them in addition that it highlight and identify the cumulative effects of harmonics on the motor performance.

KEYWORDS

Harmonics, Single-Phase Induction Motor, Inverter

الخلاصة : يتناول البحث دراسة تأثيرات المحتوى التوافقي للفولتية المحتثة من عاكسة (dc/ac Inverter) على أداء محرك حثي أحادي الطور، يتألف البحث من أجزاء نظرية و عملية تقارن أداء المحرك باستخدام فولتية جيبية و فولتية العاكس. تم استخدام مبدأ الدوائر المكافئة في عملية حساب الأداء النظري للمحرك، حيث تمت عملية تعديل على هذه الدوائر لكي تتناسب مع حساب الأداء لكل مركبات التوافقيات(Harmonic Order). إن الاستنتاج التحليلي أكد تأصل وجود العزم النبضي في المحرك الحثي أحادي الطور حتى عند تغذية المحرك بمصدر جيبي الفولتية. تم تكريس الاهتمام بالعزم النبضي للمحرك المجهز من العاكسة مع دراسة و تعريف (Pulsation) الأهم في هذه الحالة. إن مقارنة النتائج النظرية و القيم العملية بينت اتفاق جيد بالإضافة الى تركيز الاهتمام و تحديد تأثيرات تراكم التوافقيات الأكثر أهمية على أداء المحرك.

INTRODUCTION

The single-phase induction motor is widely used in low-power and variety applications such as domestic refrigerators and a wide variety of pumping applications, since this machine is logically least expensive, lowest maintenance and operates with a single-phase power supply. Almost 90 per cent of induction motors are squirrel cage rotor type, since this type of rotor has the simplest and most rugged construction imaginable and almost indestructible[1]. In special application, the dc power supply or special batteries are the main source type which only exist to drive the AC induction motor. Then, the available power has to be converted to an AC power for driving the AC induction motors, and for this aim one can use the electromechanical rotary converters or the static dc/ac converters (inverters). The last type of converter is started replacing the old rotary converters, since the use of a rotary type is associated with increase in machine size, weight and losses, while the static inverter has higher accuracy, better reliability, reduced maintenance, higher efficiency and lower in cost than the old rotary converter[2]. The output voltage waveform of the inverter is non-sinusoidal since the principle operation of the inverter is based on the switching techniques. Using the Fourier analysis shows that the output voltage and current waveforms of the inverter are rich in harmonics which may have serious problems and influences the performance of the motor. At least, the harmonics can be a source of extra losses in induction motor in addition to higher noise level.

The work presented in this study deals with steady state operation condition of the inverter-fed single-phase induction motor, and the equivalent circuit model which has been adopted in this study has been modified in order to predict the performance of the motor under load conditions.

ANALYSIS OF INVERTER-FED SINGLE-PHASE INDUCTION MOTOR

For the purpose of generality, the work presented in this study considers a single-phase induction motor fed from an inverter of a quasi-square waveform output voltage**.** Analyzing this waveform is given in Appendix[A]and shows that such a waveform which is the stator voltage of the motor which have a fundamental component and a series of harmonics. Thus, the overall performance of the motor can be described as it is connected to an independent generators all in series supplying the motor. Since each harmonic current will be independent of all the others, a series of independent equivalent circuits (one for each harmonic) can thus be used to calculate the complete steady state performance of the motor. If the magnetic saturation is neglected, the motor can be regarded as a linear device and the principle of superposition can be applied [2,3,4,5,6]. That is the motor's behavior can be analyzed independently for the fundamental and for each other harmonics term [7].

SINGLE-PHASE INDUCTION MOTOR WITH SINUSOIDAL VOLTAGE SUPPLY

The per-phase equivalent circuit referred to the stator windings (i.e. the main winding) of the single-phase induction motor for a sinusoidal voltage supply is shown in figure(1) Which realized from the symmetrical component theory. The core loss is neglected in the magnetizing branch. The magnetic flux mutual to both stator and rotor has two sequence magnetizing currents flow: I_{mp} and I_{mn}. The effect of motor speed is reflected by the presence of slip in the rotor impedance in the equivalent circuit. In this circuit the motor input impedance is given by:-

$$Z = 2Z_m + Z_{2p} + Z_{2n} \qquad (1)$$

Where:-

$Z_m = r_1 + jx_1$, $Z_{2p} = jX_m \,//\, ((r_2 / s) + j x_2)$, $Z_{2n} = jX_m \,//\, (r_2 /(2- s) + j x_2)$

The sequence currents are :-

$$I_p = I_n = V / Z \qquad (2)$$

Then, the stator winding input current is:-

$$I = I_p + I_n \qquad (3)$$

And the total input power is :-

$$P_{i/p} = V\ |I|\ \cos(\theta) \qquad (4)$$

The air-gap power is:-

$P_g = P_{gp} - P_{gn} = 2(|I_p|^2 R_{2p} - |I_n|^2 R_{2n}) = 0.5 |I|^2 [R_{2p} - R_{2n}]$ ………………(5)

While the rotor loss is :-

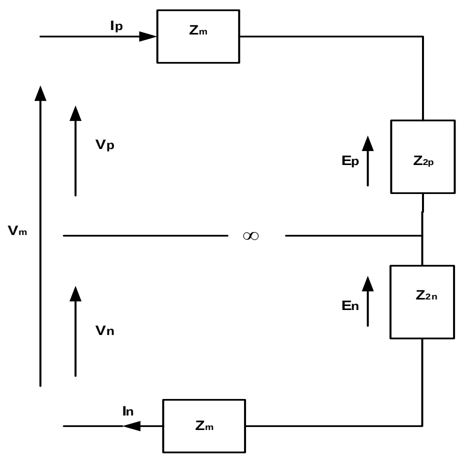
$P_{rcu} = s P_{gp} + (2-s) P_{gn}$ ……………………………………(6)

The developed gross output power is :-

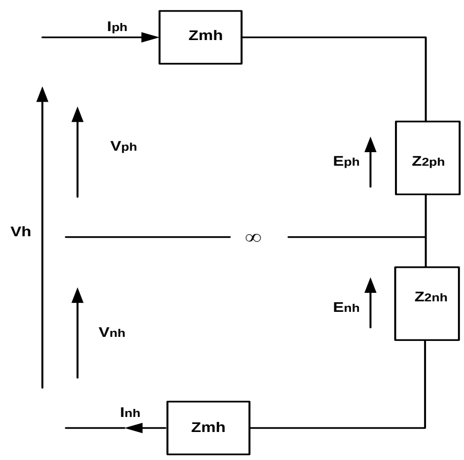
$P = (1-s) P_g$ ……………………………………………(7)

The net developed torque measured in Nm is :-

$T = P_g / \omega_s$ ……………………………………………(8)



Figure(1) Fundamental equivalent circuit of single-phase induction motor



Figure(2) The harmonic equivalent circuit of single-phase induction motor

SINGLE-PHASE INDUCTION MOTOR WITH NON-SINUSOIDAL SUPPLY

It is well know that a single-phase induction motor can be run on a non-sinusoidal supply. If the physical non-linearities of the induction motor (the magnetic saturation) is considered of negligible effects then the motor may be regarded as a linear device. Thus, the periodic non-sinusoidal supply voltage waveform could be resolved using the Fourier Series method**.** The behavior of the machine is obtained by superposing the effects of the fundamental and harmonics. This method provides information about individual harmonic performance.

According to Appendix[A], there will be no even order harmonics (i.e. $h \neq 2, 4, 6$…etc) for the quasi-square waveform, since the waveform is symmetrical. Then the only order of harmonics which exist are h=1, 3, 5……etc. and these are the only orders of harmonic that could affect the motor performance. For convenience, the existing harmonics can be expressed as:-

h (harmonic order) = $|4k \pm 1|$ ………………………………..(9)

Where k=0, 1, 2, 3….etc (constant) The harmonics of orders h=4k+1 (i.e. h=5,9,13,17,…etc) travels in the same direction as the fundamental at a speed equal to (4k+1)Ns. The harmonics of order h=4k-1 (i.e. h=3,7,11,…..,etc) travel in the opposite direction of the fundamental field with speed of rotation equal to (4k-1)Ns. Equation (9) could be written in the form for more convenience :-

$h = 1 \pm 4k$ ………………………………………………(10)

in order to specify the direction of each harmonic, too.

Frequency of Harmonic Rotor Current

The fundamental frequency equivalent circuit of the single-phase induction motor is shown in figure(1) must be modified in order to take into consideration the harmonic frequencies. This modification can be performed by introducing the following changes[3, 8]:-

1. All the reactances have a value of "h" times their value at the fundamental frequency .
2. The operation slip is the s_h.

A time harmonic of order "h" have a harmonic synchronous speed (h N_s) while the machine is rotating at speed "N_r". Thus the "h^{th}" harmonic slip of motor is :-

$$s_h = \frac{h \pm (1-s)}{h} \qquad \text{……………………………………………………..(11)}$$

Where:-
s is the fundamental slip.
s_h "h^{th}" harmonic slip of motor.
N_r rotating speed of the machine (rpm).
N_s synchronous speed (rpm).

The frequency of rotor current have positive and negative components. Then the frequency of the "h^{th}" harmonic positive sequence current component is:-

$$f_{2ph} = s_h (h \quad f_1) = (h-1+s) f_1 \qquad \text{………...…………….…….(12)}$$

while the frequency of the "h^{th}" harmonic negative sequence current component is:-

$$f_{2nh} = (2- s_h)(h f_1) = (h+1-s) f_1 \qquad \text{……………………………..(13)}$$

where f_1 is the Stator supply frequency (Hz)

Harmonic Equivalent Circuit

For any harmonic voltage (V_h) at frequency (h f_1), the rotor equivalent circuit of single-phase induction motor will appear as shown in figure(2). The parameters of the circuit are:-

$Z_{mh} = r_{1h} + j\,x_{1h}$, $Z_{2ph} = jX_{mh} // ((r_{2h} / s_h) + j\,x_{2h})$, $Z_{2nh} = jX_{mh} // (r_{2h} /(2- s_h) + j\,x_{2h})$

The rotor of the machine which is used in the work presented in this study is a cage type rotor. The crowding of current at the top of the bars increases with rotor current frequency. However the effective resistance of cage-rotor is only slightly larger than the ohmic resistance unless the bars are very deep[3, 9]. Therefore, with a low saturation level one can assume that:-

$$x_{1h} = h\,x_1 \qquad x_{2h} = h\,x_2 \qquad X_{mh} = h\,X_m \qquad r_{1h} = r_1 \qquad r_{2h} = r_2$$

Then the parameters of the circuit which shown in figure(2) will be modified as below:-

$Z_{mh} = r_1 + jhx_1$

$Z_{2ph} = (jh\,X_m) // ((r_2/ s_h)+jh\,x_2)$

$Z_{2nh} = (jh\,X_m) // (r_2/(2- s_h)+jh\,x_2)$

The positive and negative harmonic current components I_{ph} and I_{nh} are respectively given by :-

$$I_{ph} = I_{nh} = V_h / (2 Z_{mh} + Z_{2ph} + Z_{2nh}) \qquad \text{…..……..…………(14)}$$

The harmonic input current component :-

$$I_{mh} = I_{ph} + I_{nh} \qquad \text{……………………………….…………(15)}$$

Then the r.m.s value of total input current is :-

$$I_m = \sqrt{\sum_{h=1,3,5}^{h=\infty} | I_{mh} |^2} \qquad \text{……………………………………….…(16)}$$

OBVIOUS HARMONIC EFFECTS (LOSS INCREASE)

In general, harmonics are usually defined as a periodic steady state distortion of voltage and/or current waveforms in power system[10]. The effects of the harmonics are highly variable, which in range of non-significance effect to equipment destruction, but in general the harmonics always decrease both the efficiency and effective power factor of the load and the harmonics currents cause increased heating and audible noise in motors and magnetic devices[11]. Harmonic voltages produce harmonic currents that in turn, generate not only torque pulsation but also increase the losses in the form of copper and core losses. The additional losses due to the harmonics tax the thermal capability of the motor[2]. The conventional induction motor has the following losses[12, 13, 14] :-

(i) Stator copper loss;
(ii) Rotor copper loss;
(iii) Core loss;
(iv) Friction and windage loss;
(v) Stray loss.

The presence of harmonics causes the stator and rotor copper losses to increase, as for the core loss. Magnetic loss in metallic parts caused by harmonic leakage flux is difficult to estimate. It is believed that ignoring these losses can introduce negligible error compared to the harmonic copper losses[3,15]. The frictional and windage losses are independent on the harmonics [4].

Stator Copper Loss

The total harmonic current is:-

$$I_{har} = \sqrt{(|I_{m3}|^2 + |I_{m5}|^2 + \ldots + |I_{mh}|^2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(17)$$

Then the stator copper loss is (neglect the effects of the skin factor) :-

$$P_{scu} = I_m^2\ r_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(18)$$

Where I_m is the r.m.s value of total input current. Then:-

$$P_{scu} = (I_{m1})^2 r_1 + (I_{har})^2 r_1 = \sum_{h=1,3,..}^{h=\infty} P_{scuh} = P_{scu1} + \sum_{h=3,5,..}^{h=\infty} P_{scuh} \quad \ldots\ldots\ldots\ldots(19)$$

The term $[(I_{har})^2 r_1]$ is representing the extra harmonic stator copper loss. This additional losses will increase the conductor temperature due to higher current density.

Rotor Copper Loss

The rotor copper loss is evaluated independently for each harmonic. In general for each h^{th} harmonic:-

$$P_{rcuh} = 0.5\ |I_{mh}|^2\ (s_h\ R_{2ph} + (2 - s_h)\ R_{2nh}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(20)$$

The total harmonic copper loss is calculated as a summation of the harmonic contributions**.**

$$P_{rcu} = \sum_{h=1,3}^{h=\infty} P_{rcuh} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(21)$$

Also :-

$$P_{rcu} = P_{rcu1} + \sum_{h=3,5}^{h=\infty} P_{rcuh} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(22)$$

It's clear that the second term in the (22) is representing the additional rotor copper loss due to harmonic currents.

AVERAGE DEVELOPED TORQUE

The interaction between the components of the air-gap flux and the rotor current of the same harmonic frequency generates steady torques. From the harmonic equivalent circuit in figure(2), it is clear that each harmonic component produce an air-gap power (corresponding to the harmonic torque) in both positive and negative sequence directions (namely τ_{ph}, τ_{nh} respectively) acting at a speed of "h ω_s" (radian per second). The sequence component of the air-gap power is given by the following formula:-

$$\tau_{ph}\ h\ \omega_s = 2\ |I_{ph}|^2\ R_{2ph} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(23)$$

$$\tau_{nh}\ h\ \omega_s = 2\ |I_{nh}|^2\ R_{2nh} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(24)$$

Since $I_{ph} = I_{nh}$ for the motor under investigation, the "h^{th}" harmonic equivalent torque (in synchronous watt) referred to the fundamental frequency given by:-

$$\tau_h = (\tau_{ph} - \tau_{nh}) / h = 2\ |I_{ph}|^2 (R_{2ph} - R_{2nh}) / h \quad \ldots\ldots\ldots\ldots(25)$$

The order of the harmonic defines the direction of the net developed torque, and therefore the torque will act in the positive direction for the orders 1, 5, 9,….,etc, and having a positive value. For negative direction rotating fields (of order 3,7,11,….,etc,) the net torque is having a negative value (braking) and then the net develop torque due to the fundamental and harmonic current are :-

$$\tau = \sum_{h=1,3}^{h=\infty} \tau_h \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(26)$$

Obviously, τ_h becomes very small as "h" increased and thus the most important torque contribution arises from the low order harmonics.

TORQUE PULSATION

Sinusoidal Supply

With a sinusoidal supply, the input current of the single-phase induction motor, produces negative and positive sequence field components. Then in addition to the developed steady torques by these components a pulsating torque is exist with an average value of zero. The pulsation is a result of the interaction between the "fundamental" positive and negative sequence flux components with the "fundamental" negative and positive sequence rotor current components, respectively. The frequency of the generated torque is the difference between the corresponding frequency of the producing flux and currents[2,3], i.e. it is (2f). Table(1) Summaries the possible interaction of the present components with each other and the frequency of the pulsating torque or the direction of the resulting average torque, whichever is applicable. The flux components are replaced in this table by the air-gap voltages produced by them.

The general expression of the pulsation torque resulting from the different sequence field components:-

$$t_{pulsation} = t_{vn} + t_{vp} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(27)$$

where :-

$$t_{vn} = p\ L_m\ |I_{mp1}|\ |I_{2n1}|\ \sin(2wt + x) \quad \ldots\ldots\ldots\ldots\ldots(28)$$

$$t_{vp} = -p\ L_m\ |I_{mn1}|\ |I_{2p1}|\ \sin(2wt + y) \quad \ldots\ldots\ldots\ldots\ldots(29)$$

And:-

$$x = 90 - (\arg(E_{n1}) - \arg(I_{2n1})) \quad \ldots\ldots\ldots\ldots\ldots\ldots(30)$$

$$y = 90 - (\arg(E_{p1}) - \arg(I_{2p1})) \quad \ldots\ldots\ldots\ldots\ldots\ldots(31)$$

<u>Non-Sinusoidal Supply</u>

The presence of the harmonic currents can generate (in addition to the steady-torque) parasitic torques which are superimposed with the fundamental useful steady-state torque. These generated harmonic torques are two types :-

(i) Steady torque; resulting from the interaction between the harmonic current with harmonic flux of the same order. This type is usually of little importance since:-
- Harmonic currents and harmonic flux, both are relatively small in magnitude as compared to the fundamental (depends on the layout of windage).
- The forward torque produced by the positive sequence components will be partially reduced by the reverse torque that produced by the negative sequence components.

(ii) Oscillatory (pulsating) torques (with zero average value); resulting from the interaction of each harmonic current with the harmonic flux of the different orders. However, the oscillatory torques which produced by the interaction of harmonic currents with the fundamental flux (the most significant flux in the single-phase induction motor) will be predominant.

Table(2), shows a sample of the pulsation torque being considered for analysis in this study. The frequency of the pulsating torque is the difference between the frequencies under consideration[3]. From this tablehe instantaneous pulsation torque is given by:-

$$\boldsymbol{t}_{puls} = \boldsymbol{t}_{vn} + \boldsymbol{t}_{vp} \quad \ldots\ldots(32)$$

Where:-

$$\boldsymbol{t}_{vn} = p\, L_m\, |I_{mp1}|\{\, |I_{2n1}|\sin(2wt + x) + |I_{2p3}|\, \sin(2wt + i)\,\} \quad \ldots\ldots(33)$$

$$\boldsymbol{t}_{vp} = -\, p\, L_m\, |I_{mn1}|\{|I_{2p1}|\sin(2wt + y) + |I_{2n3}|\sin(2wt + e)\,\} \quad \ldots\ldots(34)$$

And:-

$$x = 90 - (\arg(E_{n1}) - \arg(I_{2n1})) \quad \ldots\ldots(35)$$

$$y = 90 - (\arg(E_{p1}) - \arg(I_{2p1})) \quad \ldots\ldots(36)$$

$$i = 90 - (\arg(E_{p3}) - \arg(I_{2p3})) \quad \ldots\ldots(37)$$

$$e = 90 - (\arg(E_{n3}) - \arg(I_{2n3})) \quad \ldots\ldots(38)$$

THEORETICAL AND EXPERIMENTAL RESULTS

The results of the simulation programs which are based on the theoretical analysis are compared with the experimental results, in order to demonstrate the validity of the theoretical model analysis. The tests with sinusoidal and inverter excitation are compared, too. The conclusions derived for such comparisons will identify the effects of feeding a single-phase induction motor upon it's operation with much more confidence. The practical measurements fall into two types, depending on the type of the supply that used to feed the motor. One of them is the sinusoidal voltage waveform while the other is the quasi–square voltage waveform. The experiments are divided into two sets of tests, each one of them measured the performance of the motor at various loads while only the main winding is in operation with rated voltage at rated frequency.

Table (1) Interaction between the air-gap flux and rotor current components in case of sinusoidal.

Stator	Rotor	Torque	Direction/frequency of pulsation
E_{p1}	I_{2p1}	Steady	Forward
E_{p1}	I_{2n1}	Pulsation	2f
E_{n1}	I_{2p1}	Pulsation	2f
E_{n1}	I_{2n1}	Steady	Backward

Table(2) Reaction of stator and rotor harmonics for nonsinusoidal

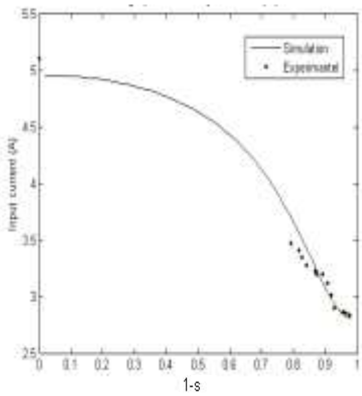
Stat	Rot	Torq	Direction/freq pulsatio
E_p	I_{2p}	Stead	Forward
E_p	I_{2n}	Pulsat	2f
E_n	I_{2p}	Pulsat	2f
E_n	I_{2n}	Stead	Backward
E_p	I_{2p}	Pulsat	2f
E_p	I_{2n}	Pulsat	4f
E_n	I_{2p}	Pulsat	4f
E_n	I_{2n}	Pulsat	2f
E_p	I_{2p}	Pulsat	4f
E_p	I_{2n}	Pulsat	6f
E_n	I_{2p}	Pulsat	6f
E_n	I_{2n}	Pulsat	4f

Operation with Sinusoidal-Waveform Supply

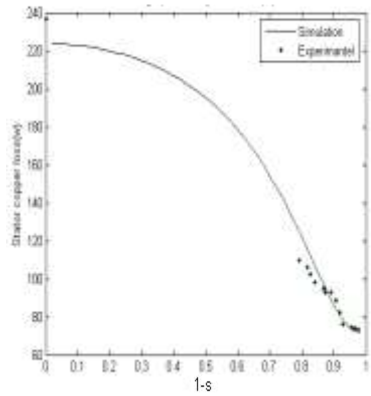
The measurements of the stator input current and the computed stator losses are plotted as a function of slip as shown in figure(3) and (4), the corresponding theoretically predicted current and losses as shown on the same figures, too. Both of these figures have a good agreement with the simulation results.

Measured and computed input power are shown in figure(5). This figure shows that the measured values slightly higher than the computed values with no more that 7% which may be attributed to neglecting of the core losses assessment in the analytical model.

The measured results of the output torque is plotted in figure(6) together with the calculated developed motor torque. The difference between the measured and calculated values is less than 14% at the worst case since the mechanical losses where not include in the mathematical model.



Figure(3) Input current



Figure(4) Stator loss

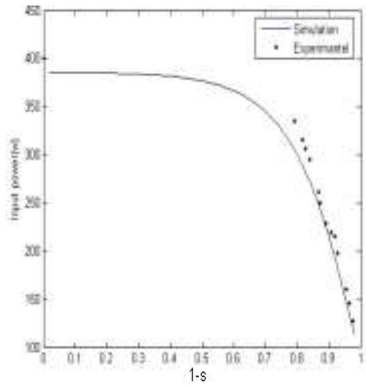
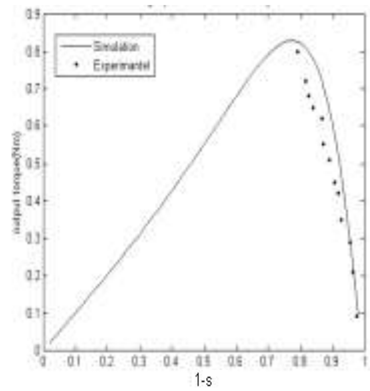


Figure (5) Input power



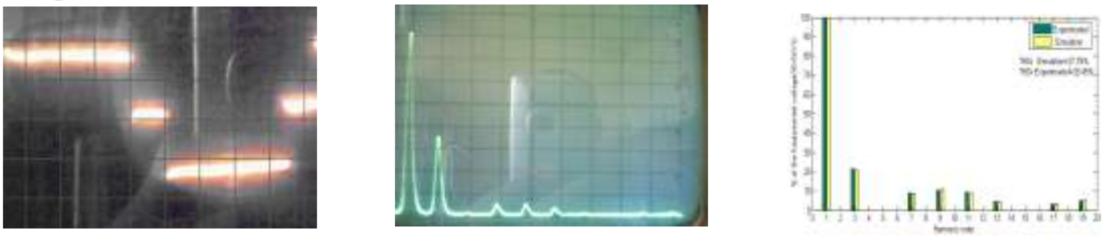
Figure(6)Output torque

Operation with Quasi-Square Waveform Supply

In this test the single-phase induction motor is supplied by a 50Hz inverter of a quasi-square waveform voltage, such that the fundamental voltage component is equal to the rated value. Figure(7.a) shows the experimental applied voltage waveform at the terminals of the motor at load conditions. Figure(7.b,c) shows that the harmonic order 5,15,…etc are not exist, since the ON-time ratio of the quasi-square voltage of the used inverter is 80%. Figures(8) and (9) show the experimental and simulation waveforms of the supply input current with it's harmonic spectrum. Good agreement between the simulation and experimental oscillogram of the input current graph is shown, noting that the simulation program plot the algebraic summation of the fundamental and harmonic spectrums of the input current up to 19th

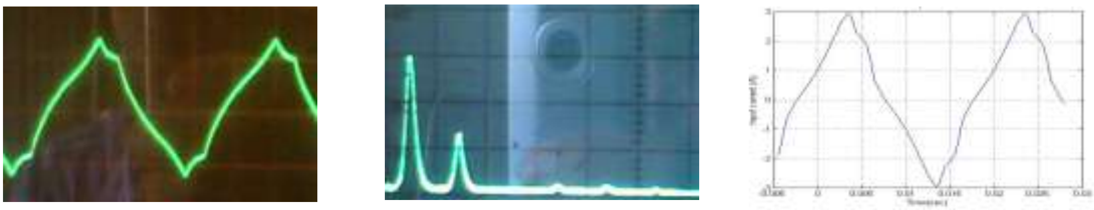
harmonic order. Inclusion of harmonics orders higher than the 19^{th} was found to be of little importance.

The supply line current harmonics as a percentage of the fundamental line current (I_h/I_1) are shown in figure(10) for different loading conditions. It shows that with load increase; the percentage harmonic current are decrease, since the increase in the fundamental current component.



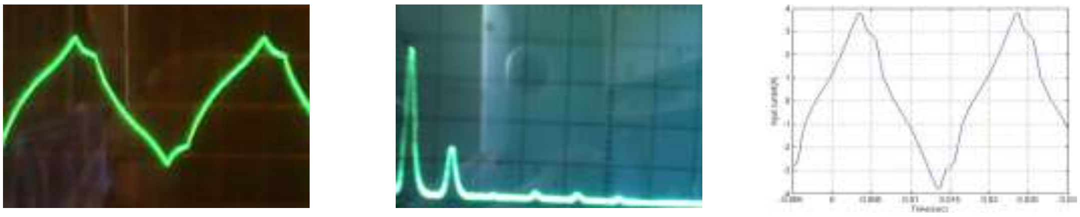
-a- -b- -c-

Figure(7) Input terminal voltage of the motor(a)Experimental waveform(100v/div,5ms/div) (b)Spectrum analyzer (c)Harmonic simulation components



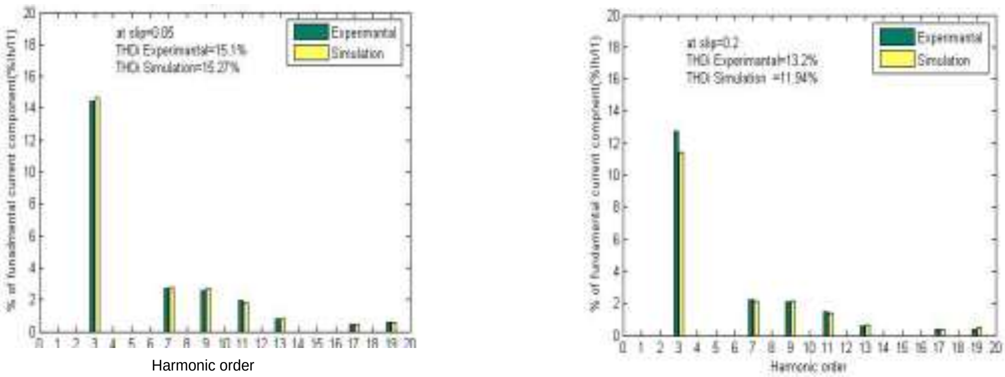
-a- -b- -c-

Figure(8) Input current to the motor at s=0.05 (a) Experimental waveform of current (2A/div, 5ms/div)(b) Spectrum analyzer(c)Simulation waveform of current



-a- -b- -c-

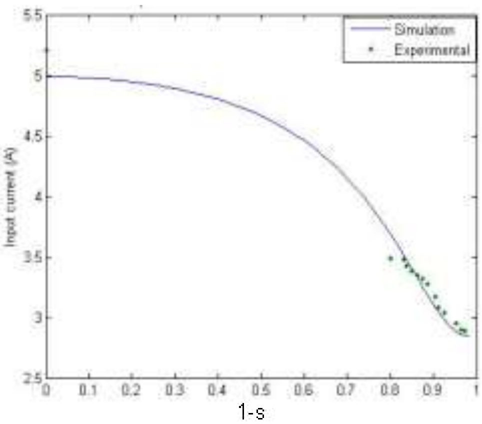
Figure(9) Input current to the motor at s=0.2 (a) Experimental waveform of current (2A/div, 5ms/div)(b) Spectrum analyzer(c) Simulation waveform of current



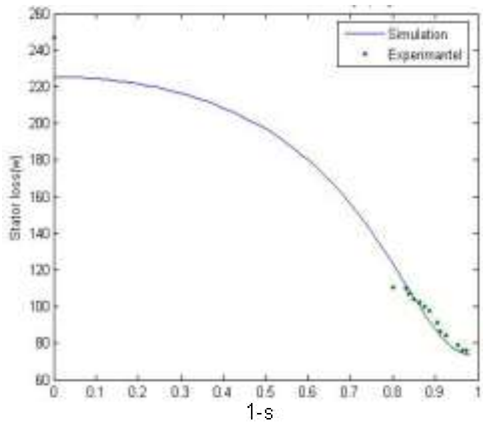
-a- -b-

Figure (10) Comparison of the simulation and experimental results of the input current harmonics as a percentage of the fundamental at (a)s=0.05, (b)s=0.2.

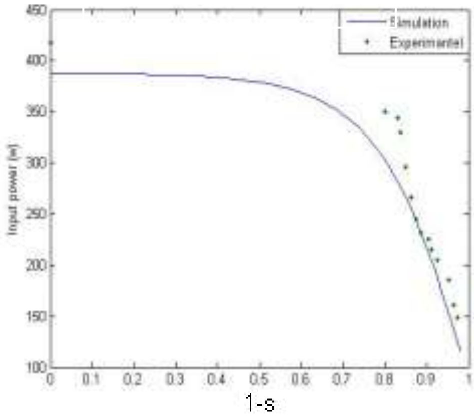
The measured and computed stator input current as a function of slip is shown in figure(11) with a good a agreement. The stator loss have slightly higher difference between the simulation and experimental results as shown in figure(12). The input power results have a significant difference between the simulation and experimental results as shown in figure(13) within 9.7% error. In figure(14) the torque measurements are lower than the computation outcomes by 18.5%. The mechanical losses are neglecting in the simulation analysis, and the difference is expected.



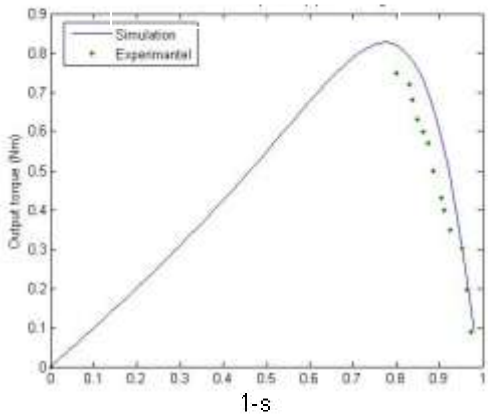
Figure(11) Input current



Figure(12) Stator loss



Figure(13) Input power

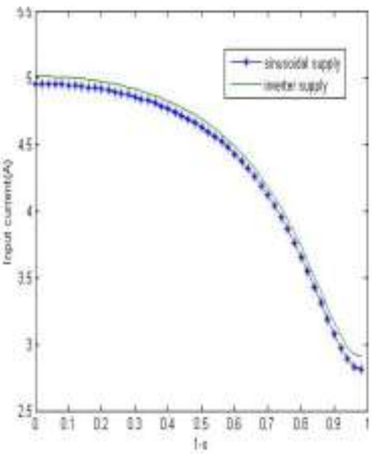


Figure(14)Output torque

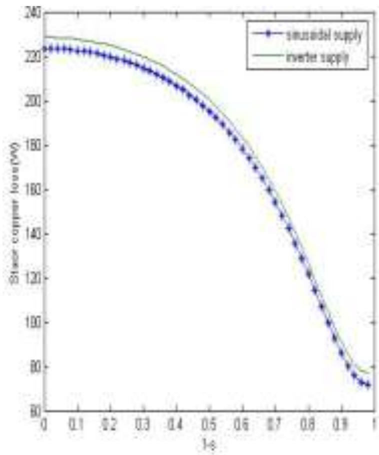
SIMULATION RESULTS

Since the experimental tests cannot be performed beyond the point of the maximum torque, it is believed that using the simulation results is very useful to determine the operational parameters of single-phase induction motor with two types of supplies down to zero speed. This will be very useful in realizing the cumulative influences of harmonics existence on the performance of motor.

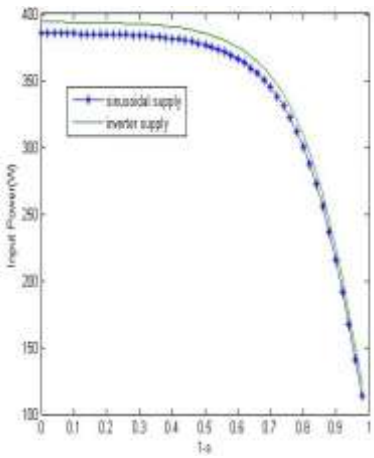
Figure(15) shows the motor input current for the two types of supplies. It is clear from this graph that there is a small increase in current due to the presence of harmonics. Figure(16) illustrates the increase in the stator loss of the motor, as a result of the increase in the rms input current, slightly greater than the sinusoidal supply. For the same reasoning, it can be noted in figure(17) the slightly difference between the simulation graph of input power.



Figure(15) Variation of Input current



Figure(16) Variation of stator loss



Figure(17) Variation of input power

The simulation results of the torque pulsation are computed for single-phase induction motor at the sinusoidal and inverter excitation, and then plotted as a functions of time for each type of feeding. It is clear from the graphs shown in figures (18) and (19), that the torque pulsation of the inverter-fed motor is larger than that of the sinusoidal supply, as a results of the presence of harmonics.

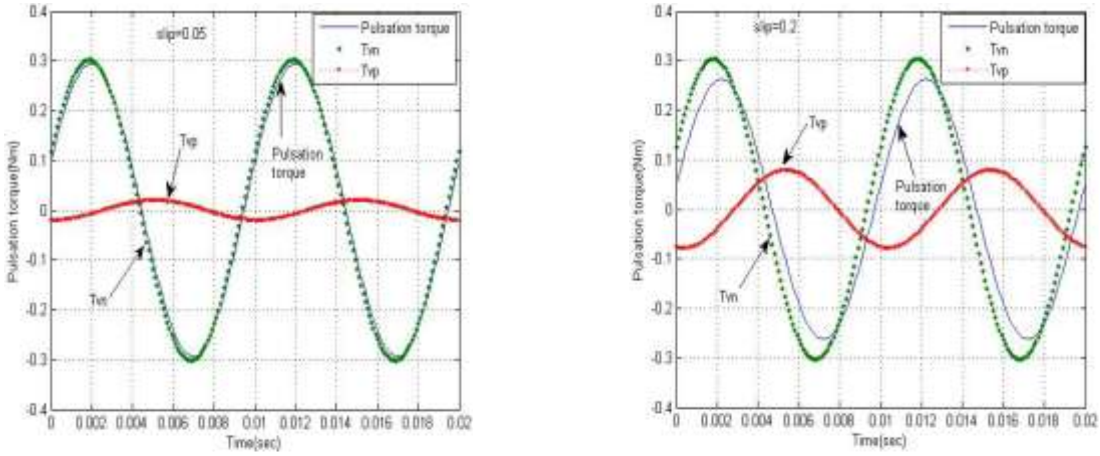
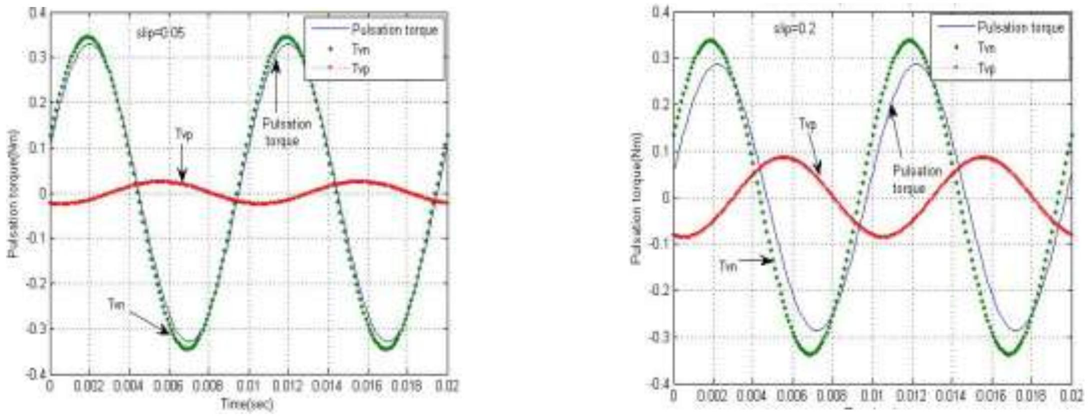


Figure (18) Instantaneous pulsation torque at different loading condition of single-phase induction motor at sinusoidal supply



Figure(19) Instantaneous pulsation torque at different loading condition of single-phase induction motor at inverter supply

CONCLUSIONS

From the comparisons of the theoretical and experimental results one can conclude that the theoretical analysis developed in this study can reasonably simulate the motor performance. The harmonics voltages and currents lead to increase in the input current, input power and motor losses and consequently lead to a drop of the efficiency as a result of the decrease in the output torque. The increase of the input power is mainly consumed in the motor as losses representing an additional source of heat, which in turn lead to increases in stator and rotor resistance and thus reduces the fundamental torque and decreasing the thermal capability of the motor. The interaction of the harmonic currents with harmonic flux of the same order produces a steady torque which could be positive or negative. However, the harmonic currents and harmonic fluxes are relatively small as compared with the fundamental and each pair of them torques are acting against each other, which may decrease each other and the net torques is too small.

The pulsation torque is inherent in single-phase motors, even when supplied from sinusoidal voltage source. With a non–sinusoidal voltage supply, the peak value of the pulsating torque is higher than that of the sinusoidal supply as a result of the presence of harmonics. The most important torque pulsation is that at two times the fundamental frequency. All the present orders of harmonics are contributing in the generation of the pulsating torque through their interaction with the other orders(including the fundamental). Thus, the torque pulsation is not confined to (2f), but higher frequency torque pulsations are also exist. However, there pulsations are of small amplitude and their net is reducing with the order of the contributing harmonic, and therefore they are of little importance.

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APPENDIX[A]

Consider the general form for the quasi-square wave, shown in figure(A.1), where **ß** is the conduction period. This rectangle waveform can be analyzed by using Fourier series using.

$$v(wt) = \begin{vmatrix} -E & -(\pi+\beta)/2 \langle wt \langle -(\pi-\beta)/2 \\ 0 & -(\pi-\beta)/2 \langle wt \langle (\pi-\beta)/2 \\ E & (\pi-\beta)/2 \langle wt \langle (\pi+\beta)/2 \end{vmatrix}$$

This function is an odd function since $v(-wt) = -v(wt)$, therefore a_h =0, i.e., no cosine term.

The function have symmetry a bout the x-axis, therefore a_0 =0, and since the wave has symmetry about each half cycle (i.e., $v(wt+\pi) = -v(wt)$) so there are no-even harmonic, therefore :-

$$b_h = \frac{2}{\pi} \int_{(\pi-\beta)/2}^{(\pi+\beta)/2} E \sin(hwt) d(wt)$$

Hence:-

$$b_h = \frac{4E \sin\left(\frac{h\beta}{2}\right)}{h\pi} \quad \text{..(A.12)}$$

The instantaneous value of "V" can be expressed as:-

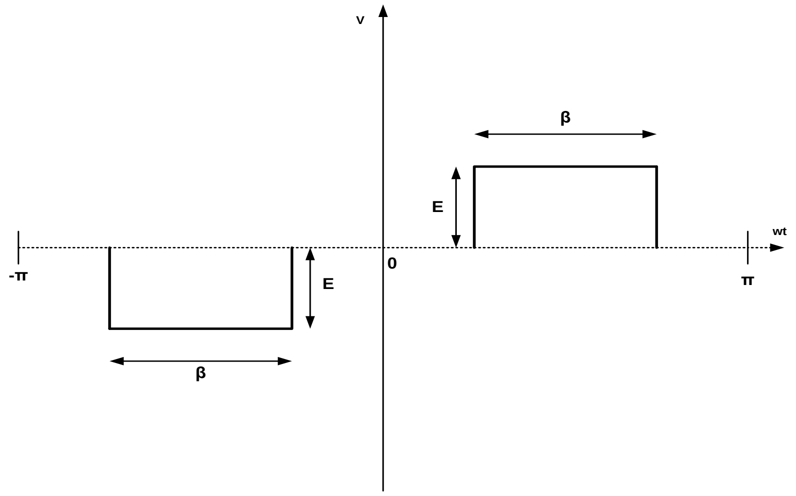
Figure(5)
Input power

$$v(wt) = \sum_{h=1,3}^{h=\infty} \frac{4E\sin\left(\frac{h\beta}{2}\right)\sin(hwt)}{h\pi} \quad \text{……………………..(A.13)}$$

The peak and rms values of the fundamental component are; respectively :-

$$\hat{V}_f = \hat{V}_1 = 4E\sin(\beta/2)/\pi \quad \text{………………..……………..(A.14)}$$

$$V_f = V_1 = 2\sqrt{2}\,E\sin(\beta/2)/\pi \quad \text{………………………….(A.15)}$$



Figure(A.1) Quasi-square waveform.

Appendix [B]
Motor and Inverter Specifications

Main winding resistance, r_{1m}, Ω	9.1
Main winding reactance, x_{1m}, Ω	11.646
Auxiliary winding resistance, r_{1a}, Ω	18.1
Auxiliary winding reactance, x_{1a}, Ω	23.7
Stator magnetizing reactance, X_M, Ω	59.4
Rotor resistance referred to main, r_2, Ω	9.59
Rotor reactance referred to main, x_2 , Ω	11.646
Turn ratio	1.15
β (ON-time rating of the output voltage of the inverter)	80%