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Derating of Synchronous Motors Fed from Polluted Supply

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ABSTRACT. Synchronous motors when fed from a power system polluted with harmonic voltages will exhibit harmonic rotating fluxes. The speed of each harmonic flux will correspond to the harmonic voltage frequency, and the direction of rotation will depend on the harmonic voltages sequence. The backward rotating fluxes (produced by the negative sequence harmonic voltages) produce braking torques. Harmonic voltages and the associated currents and fluxes result in additional copper and iron losses. Therefore, the motors, which are fed from polluted-voltage supply, should be derated otherwise the motor temperature would exceed its rated value. This endangers the windings, insulation and bearings of the motor, hence shortening its life span. In the present paper, the proper derating factors for the synchronous motors are determined when fed from polluted supply to avoid thermal stresses.

Keywords: Synchronous motors, polluted-supply, harmonics, motors derating.

1. Introduction

A major effect of voltage and current harmonics in rotating machinery (induction and synchronous) is the increased heating due to iron and copper losses. The harmonic contents thus affect the machine efficiency, and derating of the machines is necessary [1-7].

For synchronous motor each voltage harmonic induces a corresponding current harmonic in the stator of the machine. These currents will induce additional heating in the stator windings, thus adding to the temperature rise caused by the fundamental current [8]. Other generally greater concern is the flow of harmonic currents in the rotor circuits. The flow of each current in the stator will produce magnetic fluxes in the air gap that will induce current in the rotor circuits of the machine. There are two major concerns with these rotor current harmonics; (i) resultant rotor heating and (ii) pulsating or reduced torques [8].

In addition to the copper losses, additional iron losses are encountered. Due to the resulting harmonic fluxes, there will be additional stator iron losses. Also, the rotor will suffer from appreciable iron losses. These losses appear due to the relative speed between the harmonic fluxes and the rotor which rotates at the fundamental synchronous speed. Also, the rotor iron core is normally not laminated which gives a chance to increased iron losses. The main effects of the harmonics on the motor are reduction in efficiency and decrease of life of the machine which may lead to quick damage of it. Therefore, derating of the motor is necessary to avoid these problems.

2. Effect of Voltage Harmonics on the Electrical Performance

Voltage harmonics are classified as follows:

a) Positive Sequence Harmonics:

Harmonics of order $n=3k+1$; where $k=1,2,3,\ldots$, are called positive sequence harmonics. These harmonics generate rotating fluxes in the same direction of rotation of the flux produced by the fundamental voltage. Torque components produced by these harmonics are accelerating components.

b) Negative Sequence Harmonics:

Harmonics of order $n=3k-1$; where $k=1,2,\ldots$, are called negative sequence harmonics. These harmonics generate rotating fluxes in the opposite direction of rotation of the flux produced by the fundamental voltage. Torque components produced by these harmonics are decelerating components causing a braking effect on the rotor.

c) Zero Sequence Harmonics:

Harmonics of order $n=3k$; where $k=1,2,3,\ldots$, are called zero sequence or triplen harmonics. The net flux of these harmonic components in the air gap is zero. Therefore, they neither contribute in the torque output nor induce currents in the rotor.

3. Mathematical Modelling of Polluted-Supply Fed Synchronous Motor

The synchronous motor is modeled in the dqo reference frame by the circuit shown in Fig. 1 [9]. The equations governing the performance of the motor are given in the matrix form in the time domain for p.u quantities as follows [9]:

$$[v] = [R][i] + p[X][i] + \omega_m [G][i] \quad (1)$$

Where

$$[v] = [v_{ad}, v_{fd}, v_{kd}, v_{aq}, v_{kq}]^T \quad (2)$$

$$[i] = [i_{ad}, i_{fd}, i_{kd}, i_{aq}, i_{kq}]^T \quad (3)$$

[ ] (4)

[ ]

[ ] (5)

[ ]

[ ] (6)

[ ]

p is the normalized time derivative operator , and ω_m is the per-unit speed of the motor.

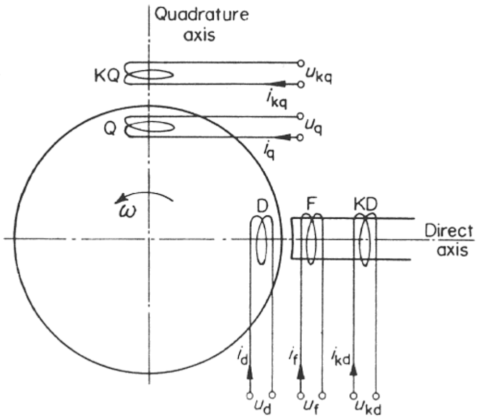


Fig. (1). DQ representation of synchronous machine

At steady-state and when the motor is fed from a polluted voltage supply while the field is fed from a pure d.c voltage, the motor equation may be split into many equation; one for the fundamental voltage and others for the harmonic voltages. For the harmonic voltages, [v] is replaced by a voltage phasor vector; [**V**], and [i] is replaced by a current phasor vector; [**I**], The time operator p is replaced by jh where h = n -1 for positive sequence voltage harmonics; i.e for n = 4, 7, 10, …while h = n + 1 for negative sequence voltage harmonics; i.e for n = 2, 5, 8, ….

The input voltage vectors are as follows:

$[\mathbf{V_1}] = [V_{ad}, V_f, 0, V_{aq}, 0]^T$, for the fundamental stator voltage and the d.c field voltage

$[\mathbf{V_n}] = [\mathbf{V}_{adn}, 0, 0, \mathbf{V}_{aqn}, 0]^T$, for the nth order stator voltage harmonic

There will be a resulting current phasor corresponding to each voltage phasor such that

$[\mathbf{I_1}]$ will correspond to $[\mathbf{V_1}]$, and is given by

$[\mathbf{I}_1] = [I_{ad}, I_{fd}, I_{kd}, I_{aq}, I_{kq}]^T$

$[\mathbf{I_n}]$ will correspond to $[\mathbf{V_n}]$, and is given by

$[\mathbf{I}_n] = [\mathbf{I}_{adn}, \mathbf{I}_{fdn}, \mathbf{I}_{kdn}, \mathbf{I}_{aqn}, \mathbf{I}_{kqn}]^T$

Each current-phasor vector can be determined independently from the others, assuming linear circuit parameters as follows:

$$[\mathbf{V_1}] = [Z_1]\,[\mathbf{I}_1] \tag{7}$$

$$[\mathbf{V_n}] = [Z_n]\,[\mathbf{I_n}] \tag{8}$$

The general forms of the components of $[Z_n]$ are as follows:

$$[R_n] = \qquad [\qquad\qquad] \qquad (9)$$

$$[X_n] = \qquad [\qquad\qquad] \qquad (10)$$

$$[G_n] = \qquad [\qquad\qquad] \qquad (11)$$

For zero sequence (n = 3, 6, 9, ..), the following equations are used

$$Z_n = (R_a + jnX_z) \qquad (12)$$

$$\mathbf{V_n} = Z_n \, \mathbf{I}_n \qquad (13)$$

X_z is the zero sequence reactance of the armature per phase.

The input voltage-phasor vector for a fundamental balanced armature applied voltage having rms value of V_1, and a field applied voltage V_f will be the conventional following vector [9]:

$$[\mathbf{V_1}] = [V_1 \sin\delta, V_f, 0, -V_1 \cos\delta, 0]^T \qquad (14)$$

Where δ is the torque angle.

For higher order positive sequence harmonic voltages (n= 4, 7, 10, ..), the input voltage-phasor vector will be as follows:

$$[\mathbf{V_n}] = [V_n , 0, 0, jV_n , 0]^T \qquad (15)$$

For negative sequence harmonic voltages (n= 2, 5, 8, ..), the input voltage-phasor vector will be as follows:

$$[\mathbf{V_n}] = [V_n , 0, 0,- jV_n , 0]^T \qquad (16)$$

4. Calculation of the Losses

The losses when the motor is fed from an ideal pure sinusoidal supply, $P_{LI,}$ are calculated as follows:

$$P_{LI} = P_{cuI} + P_{IrI} \tag{17}$$

Where, P_{cuI} is the copper losses due to the ideal condition currents, and P_{IrI} is the iron losses due to the fluxes at this ideal condition. The additional losses when the motor is fed from a polluted supply, P_{Lh} are calculated as follows:

$$P_{Lh} = P_{cuh} + P_{Irh} \tag{18}$$

Where P_{cuh} are the additional copper losses due to the resulting harmonic currents, and P_{Irh} are the additional core (iron) losses due to the flux harmonics.

4.1 Copper Losses

P_{cuI} is calculated from the following equation:

$$P_{cuI} = I_{d1}^{2} R_a + I_f^{2} R_f + I_{q1}^{2} R_a \tag{19}$$

$$P_{cuh} = \sum \tag{20}$$

4.2 Iron Losses

The air gap q- and d- axis flux-density components are directly proportional to the rotational induced voltage components in the d- and q- axes, respectively. Thus,

$$B_{dn} \,\alpha\, E_{qn} \,\alpha\, |\omega\,(L_{aq}\, \mathbf{I}_{qh} + L_{akq}\, \mathbf{I}_{kqh})| \tag{21}$$

$$B_{qn} \,\alpha\, E_{dn} \,\alpha\, |\,\omega\,(L_{ad}\, \mathbf{I}_{dh} + L_{af}\, \mathbf{I}_{fh} + L_{akd}\, \mathbf{I}_{kdh})| \tag{22}$$

a) Stator iron losses

The stator iron losses; P_{IrSn}, due to the voltage harmonic of order n are the sum of eddy current losses; P_{ESn}, and hysteresis losses; P_{HSn}.

$$P_{IrSn} = P_{ESn} + P_{HSn} \tag{23}$$

For the fundamental voltage (n = 1), $P_{IrS1} = P_{ES1} + P_{HS1}$

$$P_{En} \,\alpha\, B_n^2 f_n^2 \,\alpha\, E_n^2 f_n^2 \tag{24}$$

$P_{Hn} \,\alpha\, B_n^z f_n \,\alpha\, E_n^z f_n$, z = 1.6-2.2, and in our case h may be taken = 2, so that,

$$P_{Hn} \,\alpha\, B_n^2 f_n \,\alpha\, E_n^2 f_n \tag{25}$$

The stator iron losses due to the fundamental voltage may be split into eddy and hysteresis loss as follows:

$$P_{ES1} = a_1 P_{IrS1}, \text{ and } P_{HS1} = (1 - a_1) P_{IrS1}$$

a_1 may be found experimentally or from the design data.

Each of the eddy current losses and the hysteresis losses has two components, namely; direct-axis and quadrature-axis components. Thus

$$P_{ES1} = P_{ESd1} + P_{ESq1} \tag{26}$$

$$P_{ESd1} \propto E_{q1}^2 f_1^2$$

$$P_{ESq1} \propto E_{d1}^2 f_1^2 \tag{27}$$

$$P_{HS1} = P_{HSd1} + P_{HSq1}$$

$$P_{HSd1} \propto E_{q1}^2 f_1 \tag{28}$$

$$P_{HSq1} \propto E_{d1}^2 f_1 \tag{29}$$

Consequently, for positive and negative sequence harmonic voltages of order n

$$P_{ESdn} = P_{ESd1} (E_{qn}/E_{q1})^2 n^2 \tag{30}$$

$$P_{ESqn} = P_{ESq1} (E_{dn}/E_{d1})^2 n^2 \tag{31}$$

$$P_{HSdn} = P_{HSd1} (E_{qn}/E_{q1})^2 n \tag{32}$$

$$P_{HSqn} = P_{HSq1} (E_{dn}/E_{d1})^2 n \tag{33}$$

$$P_{IrSn} = P_{ESdn} + P_{ESqn} + P_{HSdn} + P_{HSqn} \tag{34}$$

b) Rotor Iron Losses

At stand-still, the rotor iron losses may be split into eddy and hysteresis loss as follows:

$$P_{ER1} = a_2 P_{IrR1} \text{ and } P_{HR1} = (1 - a_2) P_{IrR1} \tag{35}$$

a_2 may be found experimentally or from the design data.

Each of the eddy current losses and the hysteresis losses has two components, namely; direct-axis and quadrature-axis components. Thus

$$P_{ER1} = P_{ERd1} + P_{ERq1} \quad (36)$$

$$P_{ERd1} \ \alpha \ E_{q1}{}^{2}_{1} f^{\ 2} \quad (37)$$

$$P_{ERq1} \ \alpha \ E_{d1}{}^{2}_{1} f^{\ 2} \quad (38)$$

$$P_{HR1} = P_{HRd1} + P_{HRq1} \quad (39)$$

$$P_{HRd1} \ \alpha \ E_{q1}{}^{2}_{1} f \quad (40)$$

$$P_{HRq1} \ \alpha \ E_{d1}{}^{2}_{1} f \quad (41)$$

Consequently, for positive and negative sequence harmonic voltages

$$P_{ERdn} = P_{ERd1} (E_{qn}/E_{q1})^{2} h^{2} \quad (42)$$

$$P_{ERqn} = P_{ERq1} (E_{dn}/E_{d1})^{2} h^{2} \quad (43)$$

$$P_{HRdn} = P_{HRd1} (E_{qn}/E_{q1})^{2} h \quad (44)$$

$$P_{HRqn} = P_{HRq1} (E_{dn}/E_{d1})^{2} h \quad (45)$$

$$P_{IrRn} = P_{ERdn} + P_{ERqn} + P_{HRdn} + P_{HRqn} \quad (46)$$

It is worth to mention that the rotor eddy current losses and the rotor hysteresis losses due to the fundamental voltage both are equal to zero at the synchronous speed where the relative speed of the rotor and the flux of the fundamental voltage is zero.

The iron losses due to the zero sequence harmonic voltages are zero as the resultant main (iron) flux due to the zero sequence voltages is zero.

5. Power, Torque and Efficiency Calculations

The input power is that due to all the input voltages and the corresponding currents, in addition to the input power necessary to cover the stator and rotor iron losses. It should be kept in mind that the rotor iron losses are associated with stator to rotor power flow which, for each harmonic voltage, equals the rotor iron losses divided by the slip of the rotor with respect to the resulting rotating flux (h/n).

$$P_{in} = \sum \lceil$$

$$- \rceil \sum \quad (47)$$

where V_{dn} is the direct-axis voltage of the nth voltage component, I_{dn} is the corresponding current and Pf_{dn} is the power factor; V_{qn}, I_{qn} and Pf_{qn} are those of the q-axis; and V_{on}, I_{on} and Pf_{on} are the zero sequence values. V_f and I_f are the field coil voltage and current respectively.

The output mechanical power in this case, and consequently the output torque, contains components corresponding to the eddy currents and hysteresis energy. It is calculated as follows

$$P_m = P_{in} - (P_{cuI} + P_{IrI} + P_{cuh} + P_{Irh}) - P_{f,w} \tag{48}$$

Where $P_{f,w}$ is the friction and windage losses.

The motor efficiency is given by

$$\eta = P_m/P_{in} \tag{49}$$

The output torque is calculated using the output power as follows:

$$T_m = P_m/\omega_{syn} \tag{50}$$

Where ω_{syn} is the synchronous speed in rad/sec.

6. Derating of the Motor

The total motor losses shall not exceed their rated values in order not to exceed the thermal limits of the motor. Therefore, when there are additional losses because of the supply harmonic voltages, the motor should be derated such that the total losses are not allowed to exceed their values when the motor operates from a pure sinusoidal voltage of the rated voltage. The derating factor is defined as the ratio of the reduced load torque to the rated torque.

6.1 Method of Determination of the Derating Factor

The motor is derated by a factor determined through the following steps;

1.Variation of the motor losses with the armature current when the motor is operated from the rated pure sinusoidal voltage keeping the power factor constant is determined, and depicted in a diagram. The method of obtaining the losses curve is given in section 6.2.

2.Calculation of the motor total losses for the given terminal voltage waveform.

3.The excess losses as a result of the pollution are determined as a per-unit of the motor losses when fed from a pure sinusoidal supply. Let this to be “e”.

4.A new load value of the motor will be looked for such that the motor losses due to the fundamental voltage will be (1-e) times its normal value. This is achieved through under-loading the motor while reducing the field current to keep its power factor constant at its working value.

5. Using the losses/armature current diagrams obtained at constant power-factors, the new value of the armature current is determined. Consequently, using Eqns. 51-56, the field current is determined.

6. The new output power and torque are, then, calculated using Eqn. 47-50.

7. Using the calculated torque, the corresponding derating factor is calculated.

6.2 Losses Curves

The motor losses when the motor is fed from a pure sinusoidal supply may be calculated at different field currents and developed torques with the power factor as a parameter as follows:

- At an assumed value of the armature current at a certain power factor, the torque angle (δ) can be calculated from the following formula [1]:

$$\tan \delta = - (I_a X_q \cos \theta + I_a R_a \sin \theta)/(V_1 + I_a X_q \sin \theta - I_a R_a \cos \theta) \quad (51)$$

where, θ is the power factor angle.

- Hence, the field current is calculated as follows:

$$I_d = I_a \sin (\delta - \theta) \quad (52)$$

$$I_q = - I_a \cos (\delta - \theta) \quad (53)$$

$$V_d = V_1 \sin \delta \quad (54)$$

$$V_q = - V_1 \cos \delta \quad (55)$$

$$I_f = (- V_q - I_d X_d + I_q R_a)/X_{af} \quad (56)$$

The total copper losses and iron losses are then calculated as explained in section 4 for the case of an ideal pure sinusoidal supply.

This is repeated at other values of power factors, and diagrams giving the motor total losses against the armature current for different power factors are plotted.

7. Results and Discussions

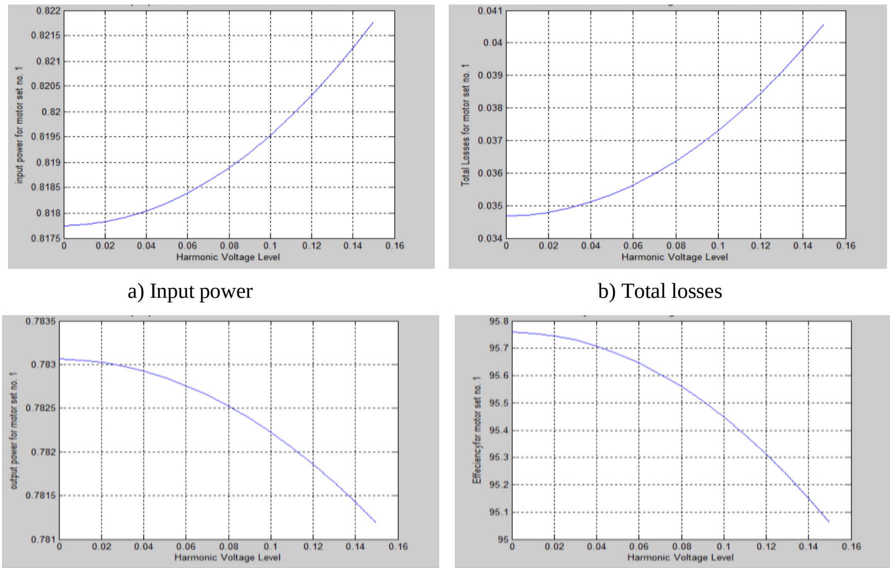
A computer program has been developed to calculate the current phasors in the motor circuits corresponding to the fundamental voltage and the imposed voltage harmonics. Also, the program calculates the derating factor. The program enables the calculations for different ratings and motor types supplied with voltage waveforms of different levels of distortion. Two different salient-pole synchronous motors have been investigated. The first motor is 494 kVA, 12 pole and the second motor is 831 kVA, 6 pole. The parameters of the two motors used in the calculations are given in Appendix A.

In order to investigate the effect of certain harmonic content on the derating factor of the motor, harmonic component of orders 2 to 7 have been included individually in the voltage waveform at six levels of voltage harmonic distortion factors (VHF); 2.5%, 5%, 7.5%, 10%, 12.5% and 15%. The motor input power, total losses, output mechanical power and efficiency against the voltage distortion factor were calculated at the different VHF for each harmonic voltage component.

The calculations have shown that lower order harmonic components, specially the 2nd and 3rd harmonic components, have the worst effect on the motor losses and efficiency and hence the derating factor.

Figs. 2-4 show the variation of the input electrical power, total losses, output mechanical power, and efficiency for the first synchronous motor (494 kVA, 12 pole) fed by a distorted voltage waveform up to 15% VHF for the 2nd, 3rd and the 4th harmonic components as examples. Figs. 5-7 show the same curves for the second motor (831 kVA, 6 pole).

For the same distortion level, the 3rd harmonic gave the worst efficiency and losses. This is due to the low zero sequence impedance experienced by the synchronous motor which results in high stator currents, and consequently high copper losses. The 2nd harmonic voltage comes secondly. This is because the 2nd harmonic causes stator copper losses and iron losses in both the stator and rotor. Also, this harmonic, being a negative sequence component, has a braking effect which absorbs mechanical power from the shaft and converts it to copper losses in the rotor [10-11].



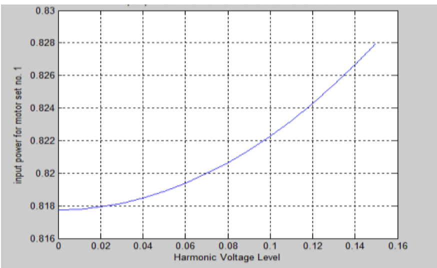
a) Input power

b) Total losses

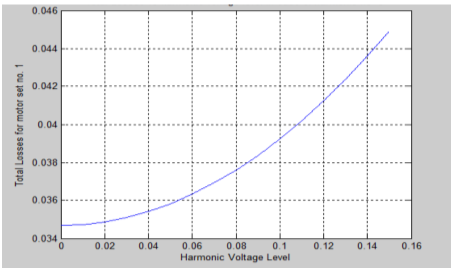
c) Output mechanical power

d) Efficiency

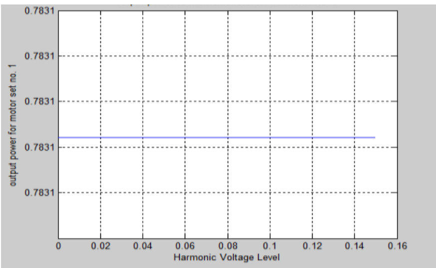
Fig. (2). Effects of the level of the second harmonic voltage on the first-motor performance



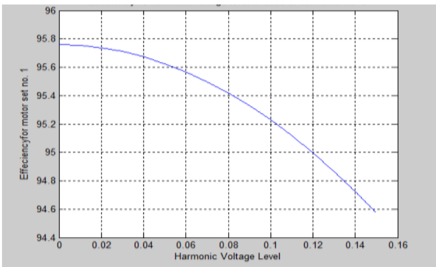
a) Input power



b) Total losses

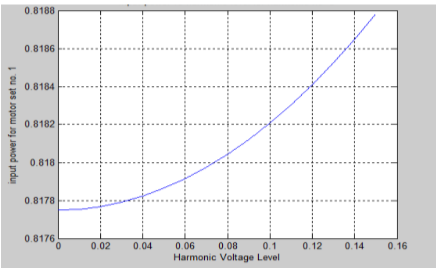


c) Output mechanical power

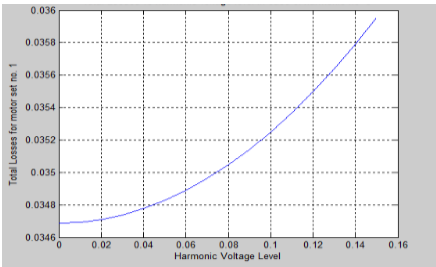


d) Efficiency

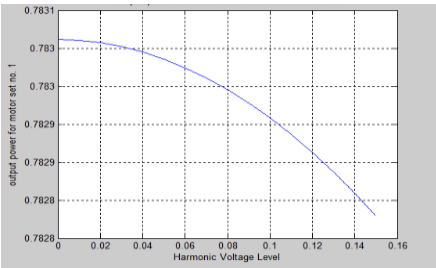
Fig. (3). Effects of the level of the third harmonic voltage on the first-motor performance



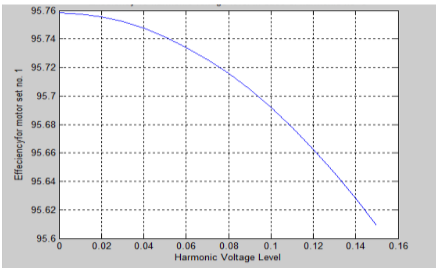
a) Input power



b) Total losses

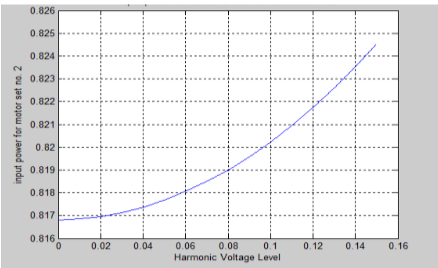


c) Output mechanical power

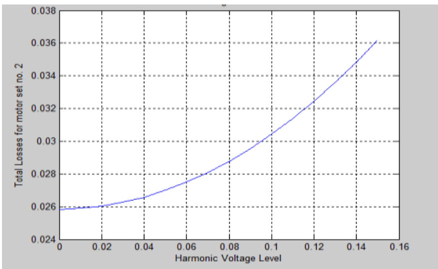


d) Efficiency

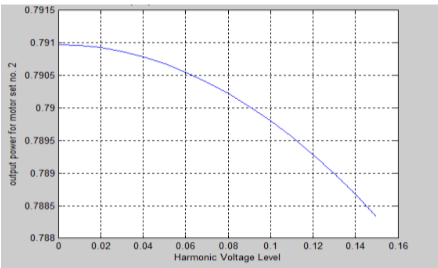
Fig. (4). Effects of the level of the fifth harmonic voltage on the first-motor performance



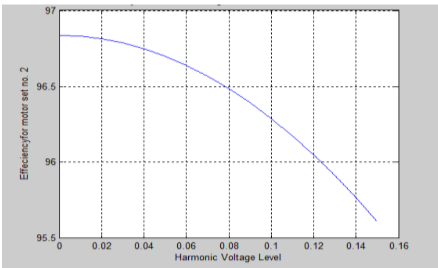
a) Input power



b) Total losses

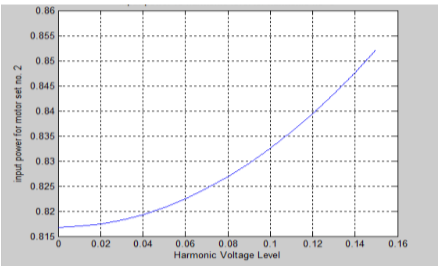


c) Output mechanical power

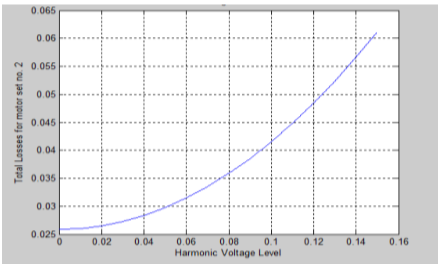


d) Efficiency

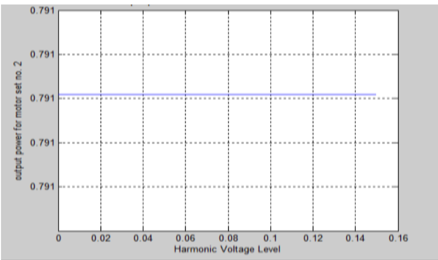
Fig. (5). Effects of the level of the second harmonic voltage on the second-motor performance



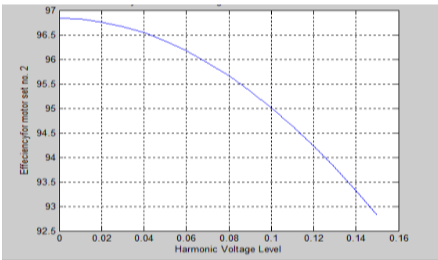
a) Input power



b) Total losses

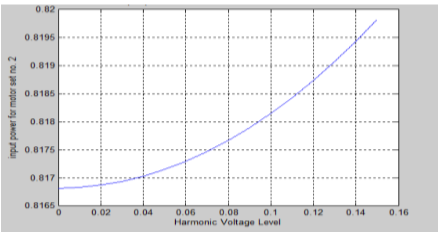


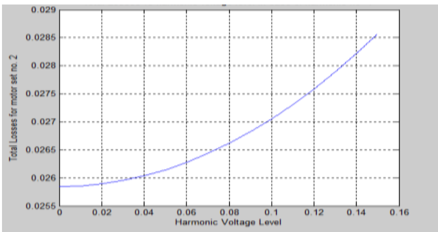
c) Output mechanical power



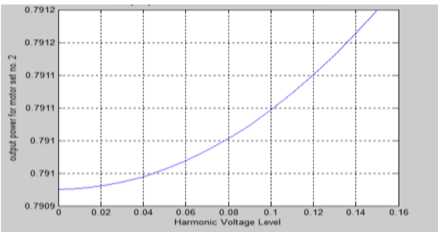
d) Efficiency

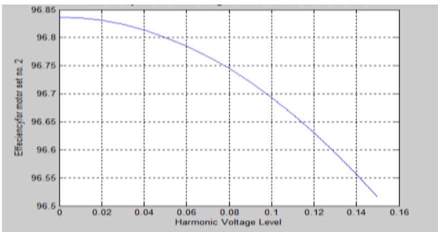
Fig. (6). Effects of the level of the third harmonic voltage on the second-motor performance





a) Input power b) Total losses

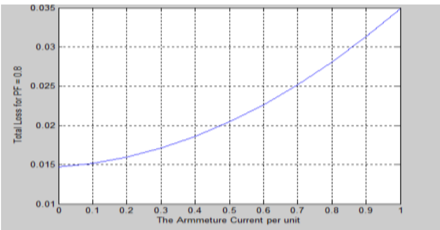


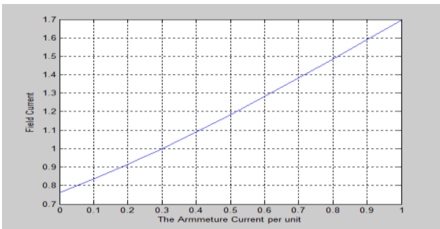


c) Output mechanical power d) Efficiency

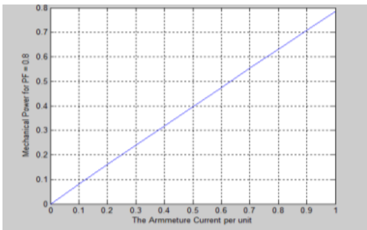
Fig. (7). Effects of the level of the fourth harmonic voltage on the second-motor performance

To help in calculating the derating factors the performance characteristics of the synchronous motors, when derated (operated at reduced armature current) keeping the power factor constant at the rated value, were calculated. These performance characteristics are shown in Figs. (8 and 9).



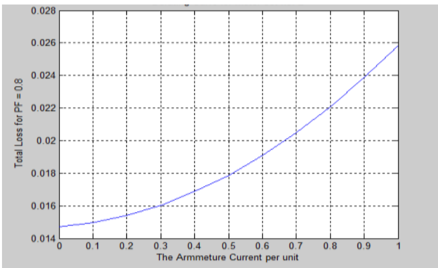


a) Variation of the losses with the armature current b) Variation of the field current with the armature current at constant power factor

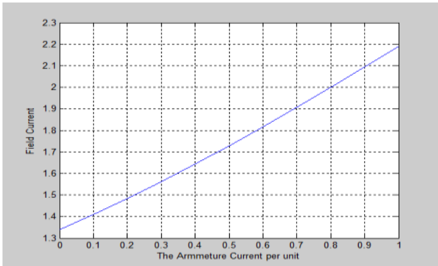


c) The output mechanical power versus the armature current at constant power factor

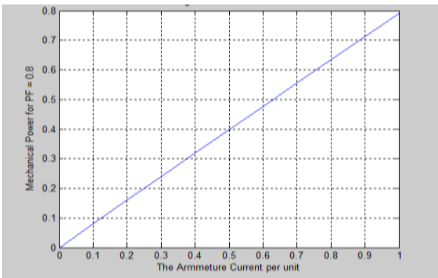
Fig. (8). Derating performance characteristics of the first motor



a) Variation of the losses with the armature current



b) Variation of the field current with the armature current at constant power factor



c) The output mechanical power versus the armature current at constant power factor

Fig. (9). Derating performance characteristics of the second motor

With the help of all the curves of figures (2-9) the derating factors are calculated for the different voltage harmonics at 0.15 VHF for the two synchronous motors. The results are shown in Tables (1 and 2).

Table (1). Derating factors of the first motor.

Harmonic order	2^{nd}	3^{rd}	4^{th}	5^{th}	6^{th}	7^{th}
Motor armature current, p.u	0.85	0.68	0.9	0.92	0.89	0.98
Motor field current, p.u	1.55	1.37	1.6	1.62	1.59	1.68
Derating Factor	0.856	0.69	0.92	0.923	0.91	0.988

Table (2). Derating factors of the second motor.

Harmonic order	2^{nd}	3^{rd}	4^{th}	5^{th}	6^{th}	7^{th}
Motor armature current, p.u	0.27	******	0.85	0.91	0.35	0.95
Motor field current, p.u	1.53	******	2.05	2.10	1.64	2.14
Derating Factor	0.272	******	0.8514	0.911	0.352	0.9505

****** The motor can’t be operated even at no-load.

It is clear that the zero sequence voltages have the worst effect. The negative sequence voltages come after the zero sequence. The positive sequence voltages have the least effect.

8. Conclusion

A detailed study has been conducted in this paper to investigate the electro-mechanical performance of three phase synchronous motors, of different ratings, when fed from a polluted voltage supply. The synchronous motor at steady state has been deeply studied. An accurate method for calculating the derating factor based on developed equivalent circuits for the synchronous motors have been presented. The method is based on constraining the output power and torque of the motor such that the total losses (copper plus iron) due to the fundamental voltage and the voltage harmonics do not exceed the losses of the motor when operates from pure sinusoidal voltage at its rated conditions. The calculations have been carried out for different types and rating of synchronous motors at different percentages of individual harmonic components. The program outputs confirmed the following points:

- Synchronous motors are much more sensitive to the 3rd and 2nd harmonic orders than to any other orders.

- If at a certain percentage of distortion the no load losses exceed the rated losses, the motor should not be allowed to operate.

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Acknowledgment

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Appendix A: Motors Parameters

The first motor is 494 kVA, 12 pole and the second motor is 831 kVA, 6 pole. The parameters of the two motors in p.u are given in Table (3).

Table (3). Parameters of the synchronous motors

Parameter	First motor	Second Motor
	0.01502	0.00877
	0.00168	0.00064
	0.02799	0.00677
	0.02858	0.00877
	1.51941	0.85555
	1.31151	0.74650
	0.96484	0.56425

Continue table (3).

Parameter	First motor	Second Motor
	1.40107	0.82680
	0.81911	0.48401
	0.77027	0.43772
	0.73504	0.42615
	0.50897	0.31940
	0.47556	0.29929

Iron losses at rated voltage and speed for the first motor = 0.015 p.u

Iron losses at rated voltage and speed for the second motor = 0.0149 p.u

تخفيض قدرة المحركات المتزامنة المغذاة من مصدر جهد ملوث

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)قدم للنشر يف 0202/7/02م؛ وقبل للنشر يف 0202/9/07م(

ملخص البحث. نظراً لالنتشار املطرد لتطبيقات إلكترونيات القوى باإلضافة إىل األحمال الكهربائية الالخطية، فقد باتت الشبكة الكهربائية ملوثة بالتوافقيات من مجيع الرتب. ولقد عكف الباحثون مؤخراً على دراسة تأثري هذه التوافقيات على عناصر الشبكة الكهربية املختلفة، ومن بني هذه العناصر احملركات املتزامنة. ميثل هذا البحث جزءاً من اجلهود املبذولة لتحديد رتبة التوافقيات األكثر تأثرياً على احملركات املتزامنة، وحساب معامل خفض القدرة للمحركات املتزامنة عند تغذيتها من مصدر جهد ملوث بالتوافقيات.

ويبدأ البحث بدراسة عن التوافقيات ومصادرها على الشبكة، ومن ثم ننتقل ملناقشة األداء الكهربي وامليكانيكي للمحرك يف مرحلة التشغيل املستقر (Steady State). وسيتم اقتراح منوذجاً معدالً للمحرك املتزامن يف اطار حماور الر dqo يأخذ بعني االعتبار الفقد احلديدي يف كل من العضو الثابت والعضو املتحرك للمحرك. ومن ثم نقترح طريقة جديدة حلساب كل من معامل ختفيض القدرة ومعامل. ولقد مت تطبيق البحث على أنواع خمتلفة وكذلك أحجام خمتلفة من احملركات املتزامنة ومت اجراء بعض القياسات والتجارب للتحقق من تأثري تواجد توافقيات اجلهد على درجة حرارة احملركات.