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Coupling induction motors to improve the energy conversion process during balanced and unbalanced operation

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ABSTRACT

This paper assesses the steady-state performance of cascaded IMs (induction motors) operating under voltage unbalance. Small sizes induction motors are connected in cascade instead of one big size induction motor to improve the electromagnetic system and to make the energy conversion process more efficient during both balanced and unbalanced operation. The two mechanically coupled induction motors could have the same ratings or different ratings. The paper analyzes the coupled machines system using the method of symmetrical components and MATLAB/Simulink software. The definition of the voltage unbalance using CVUF (complex voltage unbalance factor) is used. Coupling of induction motors with DC (direct current) motors is examined to investigate the effect of cascading on the electromagnetic torque of the entire set. A comparison of the effect of the unbalanced voltage on single and cascaded machines is illustrated. The purpose of such comparison is to determine which one has the best performance during the balanced and unbalanced operations. Furthermore, this paper assesses the impact of connecting induction motors in cascade on the energy conversion process.

1. Introduction

The induction motor is as considered one of the most popular motors in the industry; it should be used properly to save the energy consumed and to improve the performance [1,2]. Thus, this paper studies the use of cascading small sizes induction motors instead of one big size induction motor to improve the electromagnetic system and the energy conversion process [3]. The electromagnetic forces act between the rotor and the stator where the magnetic flux density is different in the big size induction motors than the small sizes induction motors connected in cascade wherein the rating summation thereof is the same rating of the big size induction motor [4].

The cascaded induction motors herein, deemed to be two coupled induction motors, are cascaded on the same shaft and feed the same load. The machine coupling is either a magnetic coupling or electrical coupling. Although the same torque is transferred to the load, the energy conversion process is changed and the efficiency is different.

Voltage unbalance is a power quality problem, it is a common phenomenon found in a three-phase power system. Although the three-phase voltage supply is balanced in both magnitude and phase-angle at the generation and transmission level, the voltage at the load terminal and utilization side could become unbalanced [5–7]. It is practically impossible to obviate such unbalance due to the uneven distribution of single-phase loads in the three-phase supply system, asymmetric transmission line and transformer winding impedances. Such condition has severe impacts on the performance of an induction motor [8]. This motor can tolerate a low degree of voltage unbalance, so the unbalance should be derated if it is excessive [9]. The voltage unbalance can increase stator and rotor losses in the induction motor, rise windings temperature, reduce the insulation life caused by overheating, and derate its output horsepower, so it cannot tolerate the extra heating arising from the unbalanced voltage supply. It is worth mentioning that the unbalanced conditions are two cases; at over-voltage and at under-voltage [10]. From this point of view, the paper studies replacing one big size induction motor with small size induction motors to reach the best performance throughout the unbalanced operation.

2. Definition of CVUF (complex voltage unbalance factor)

VU (voltage unbalance) has been examined by some researches explained in Ref. [11]. In most previous studies, the method of evaluating the degree of unbalanced voltage is based on either NEMA (National Electrical Manufactures Association) standard or IEC (International Electrotechnical Commission) definition. Both

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List of symbols

CVUF	complex voltage unbalance factor
V_{ab}, V_{bc}, V_{ca}	stator line voltages
V_a, V_b, V_c	stator phase voltages
kv	magnitude
θ_u	angle of the CVUF
V_{s1}	positive sequence voltage
V_{s2}	negative sequence voltage

the NEMA and the IEC definitions are only considering the magnitude of the voltage unbalance to describe the degree of unbalanced voltage. The three-phase voltage supply has not only magnitude but also phase-angle that gives contribution to the voltage unbalance. Hence, both the definitions lead to a comparatively large error in predicting the performance of the induction motor.

A more precise approach in predicting the performance of an induction motor operation with unbalanced three-phase voltage is by using the complex quantity to specify the degree of voltage unbalance. This definition was recently known as the complex unbalance voltage factor and is used as CVUF in the most recent literature [11]. So, the CVUF is an extension of the IEC definition which consists of magnitude and angle of the voltage unbalance.

Analysis of inductions motor operating with unbalanced voltage supply using are done in this paper by using symmetrical component approach and by MATLAB/Simulink modeling program.

2.1. Analysis of the induction motor which operates with unbalanced voltage supply

The analysis is done using the symmetrical component approach that requires positive and negative sequence equivalent circuits

$$V_{ab} = V_a - V_b \tag{1}$$

$$V_{bc} = V_b - V_c \tag{2}$$

$$V_{ca} = V_c - V_a \tag{3}$$

$$V_{s1} = \frac{1}{3} * \left(V_{ab} + a * \mathrm{V}_{bc} + a^2 * V_{ca}\right) \tag{4}$$

$$V_{s2} = \frac{1}{3} * \left(V_{ab} + a^2 * V_{bc} + a * V_{ca}\right) \tag{5}$$

The CVUF is defined as shown Eq (6), where K_u is the magnitude and θ_u is the angle of the CVUF.

$$K_u = \frac{V_{s2}}{V_{s1}} = K_u < \theta_u \tag{6}$$

In contrary, the line voltages can be obtained from their positive and negative sequence.

$$\begin{aligned} V_{ab} &= V_{s1} + V_{s2} \\ V_{bc} &= a^2 \times V_{s1} + a \times V_{s2} \\ V_{ca} &= a \times V_{s1} + a^2 \times V_{s2} \end{aligned} \tag{7}$$

If the ratio of line-voltages is defined by:

$$V_{ab} : V_{bc} : V_{ca} = 1 : X : Y \tag{8}$$

Then, the relation between (K_u, θ_u) and (X, Y) is:

$$X = \frac{1 + K_u}{a^2 + a * K_u} \tag{9}$$

$$Y = \frac{a + a^2 * K_u}{a^2 + a * K_u} \tag{10}$$

where K_u and θ_u are the magnitude and angle of CVUF of the phase voltage respectively. The angle, θ_u indicates the angle by which V_{s2} leads the V_{s1}, and it is an important parameter to decide the pattern of voltage under different condition of unbalance, whereas k_u is the measurement of the intensity of severity. Normally the V_{s1} is very close to unity in per unit k_u will be very close to V_{s2}.

Assume three phase voltage source balanced with 460 V_{L-L} supplied three phase induction motor the values of X and Y for different K_u and θ_u are illustrated in Tables 1 and 2.

Fig. 1(a) illustrates the positive and negative sequence equivalent circuit for the induction motor supplied by unbalanced supply and Fig. 1(b) illustrates the complex voltage unbalance factor (CVUF) diagram.

Fig. 1(b) was obtained from using Eqs (9) and (10). The relation between (K_u, θ_u) and (X, Y) with constant K_u and varies θ_u from (0–360), the loci shown in $(X - Y)$ plane looks like ellipse. Using the relation between (K_u, θ_u) and (X, Y) with constant θ_u and varies K_u the loci shown in $(X - Y)$ plane looks like straight line.

3. Torque/slip characteristic for 50 hp (37,300 W) induction motor at balanced and unbalanced supply voltage

The symmetrical component theory approach is used to analyze the operation of induction motor under such conditions. MATLAB/Simulink program is employed for computer simulation [11–14].

Fig. 2 illustrates the difference between the torque/slip characteristic for 50 hp (37,300 W) induction motor. The impact of the balanced and unbalanced supply voltage is shown. It is noted that the torque decreases for different values of the unbalanced voltage that can be explained by the unbalance voltage produce negative sequence torque decreases the resultant torque.

4. Torque/slip characteristic for the standalone and two coupled motors in balanced and unbalanced cases

In this section, two induction motors are connected in cascade either through mechanical coupling or electrical coupling. The

Table 1
Data of (X, Y) for different values of K_u.

$K_u = 1.69\%$		$K_u = 3.45\%$		$K_u = 5.26\%$		$K_u = 7\%$	
X	Y	X	Y	X	Y	X	Y
0.98	0.98	0.95	0.95	0.93	0.93	0.90	0.90
0.97	0.99	0.94	0.97	0.91	0.96	0.89	0.94
0.97	1.00	0.95	1.00	0.92	1.00	0.90	1.00
0.99	1.01	0.97	1.02	0.95	1.04	0.94	1.06
1.00	1.03	1.00	1.05	1.00	1.08	1.00	1.11
1.01	1.03	1.03	1.06	1.05	1.10	1.07	1.13
1.03	1.03	1.05	1.05	1.08	1.08	1.11	1.11
1.03	1.01	1.06	1.03	1.10	1.05	1.13	1.07
1.03	1.00	1.05	1.00	1.08	1.00	1.11	1.00
1.01	0.99	1.02	0.97	1.04	0.95	1.06	0.94
1.00	0.97	1.0	0.95	1.00	0.92	1.00	0.90
0.99	0.97	0.97	0.94	0.96	0.91	0.94	0.89
0.98	0.98	0.95	0.95	0.93	0.93	0.90	0.90

Table 2
Data of (X, Y) for different values of θ_u.

$\theta_u = 120$		$\theta_u = 300$	
X	Y	X	Y
0.97521	0.97524	1	1
0.95055	0.95054	1.02586	1.02583
0.92609	0.92614	1.05390	1.05391
0.90407	0.90459	1.08429	1.08425
0.88000	0.88000	1.11413	1.11357

rating of each one is 25 hp (18,650 W), so the entire rating of the set is 50 hp (37,300 W) which equals the rating of one big standalone induction motor for comparison purpose. The parameters of the machines are different, so different characteristics are expected. In Fig. 3 the torque speed characteristic of the two coupled motors is higher in the balanced operation. Also in Figs. 4–7.

From the above curves, it is obvious that applying unbalance voltages to the three phases induction motor decreases its maximum energy conversion value which is directly proportional to the output torque, and shifts the torque speed characteristic down which forces to de-rate the machine to avoid the motor burnout.

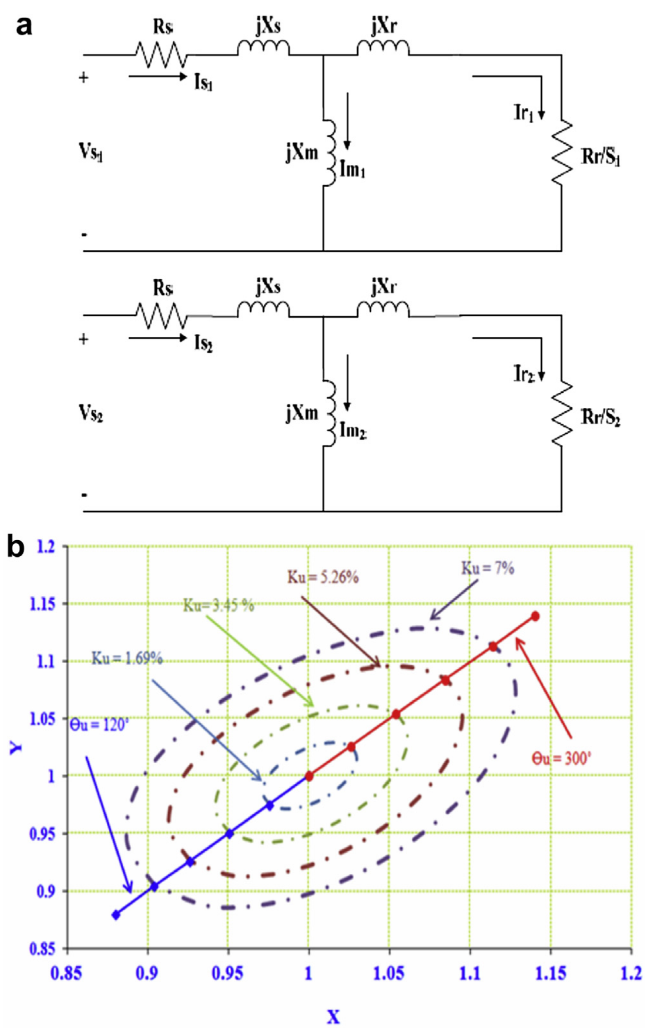

Fig. 1. (a) Sequence equivalent circuit. (b) Complex voltage unbalance factor (CVUF) diagram.

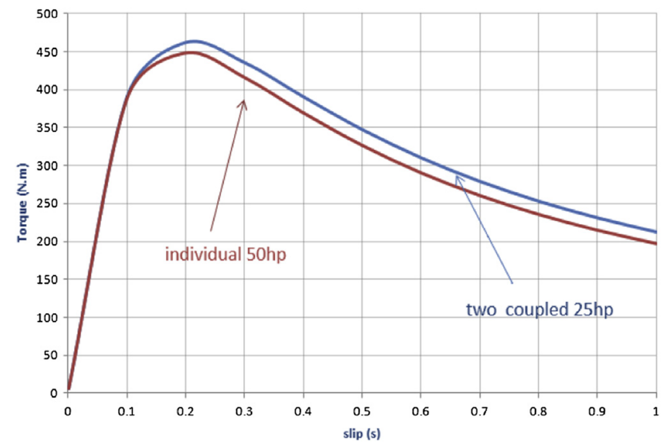

Fig. 3. Torque/speed characteristics for balanced case.

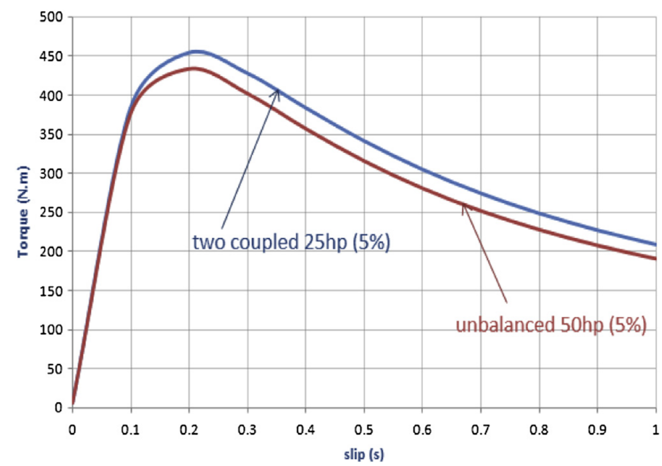

Fig. 4. Torque/speed characteristics for 5% CVUF.

Also the group of cascaded induction motors is better than the standalone motor with the same rating in case of applying unbalanced voltages i.e.: gives higher energy conversion.

In addition, it is noticed that applying unbalanced voltages with CVUF of 5% up to 20% affects the motor slightly which proves that until 20% unbalance can be considered as an acceptable range for operating motor without numerous damage.

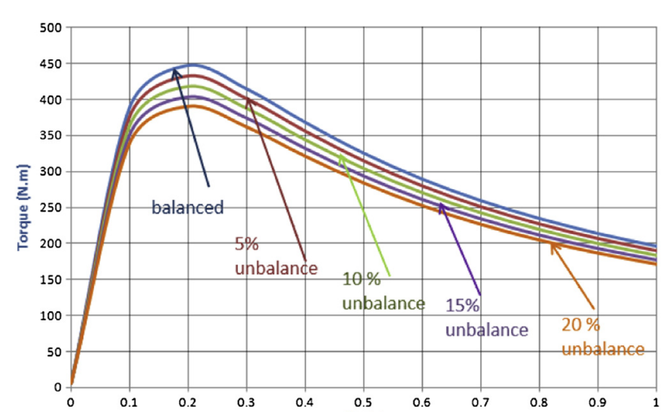

Fig. 2. Effect of the balanced and the unbalanced on the torque/speed characteristic.

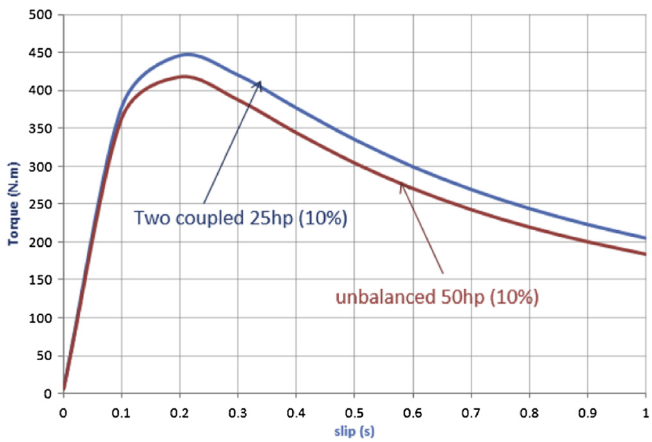

Fig. 5. Torque/speed characteristics for 10% CVUF.

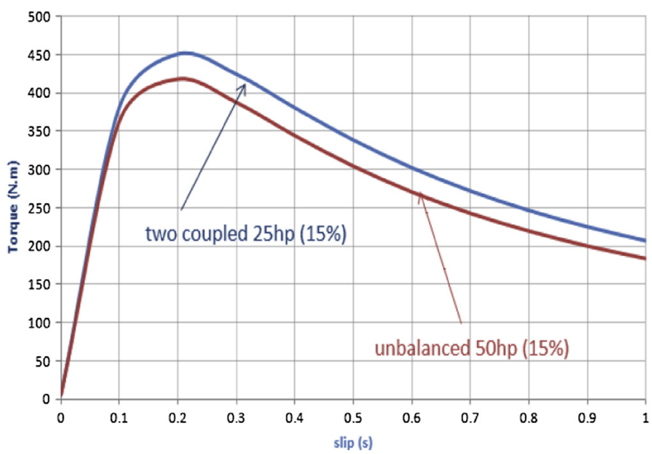

Fig. 6. Torque/speed characteristics for 15% CVUF.

5. Cascading the induction motor with DC motor

The torque/speed characteristic of any induction motor has a general fixed shape. Hence, to improve the electromagnetic system and the energy conversion process, the induction motor must be cascaded with another type of electrical machines to obtain a new electromagnetic system that has better energy conversion process.

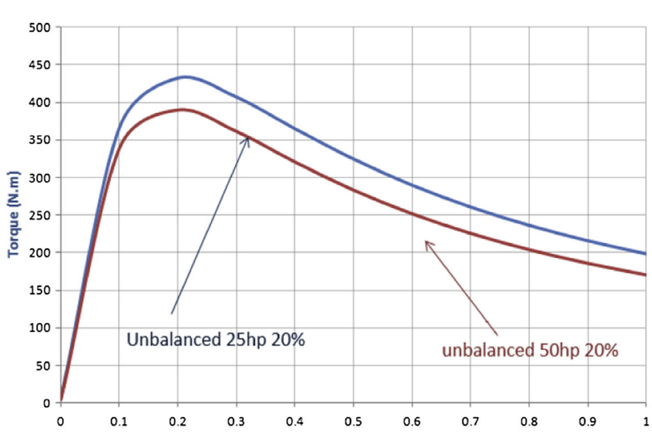

Fig. 7. Torque/speed characteristics for 20% CVUF.

Table 3
Shows data of induction motor of first cascading.

hp	W	V_{L-L}	$2P$	R_1	R'_2	X_1	X_2	X_m	F(Hz)
25	18,650	460	4	0.641	0.332	1.106	0.464	26.360	60
30	22,380	400	4	0.73	0.16	0.16	0.16	14.96	60

Table 4
Shows data of the DC motor of first cascading.

hp	W	V_t	R_a	R_F	I_F	K	W_{rated}
5	3730	240	2.581	281	1.06	0.9383	1750

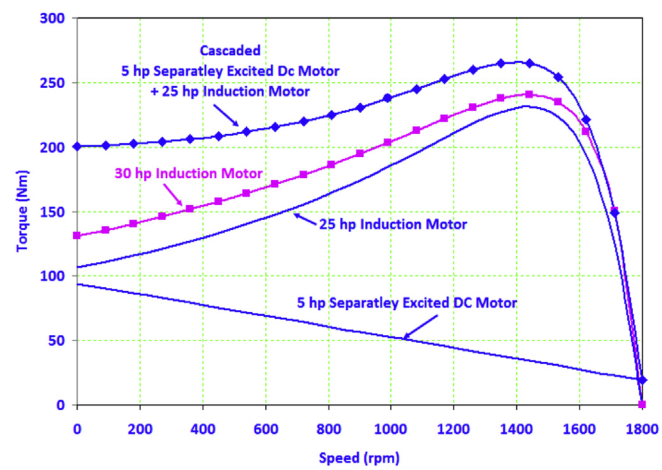

Fig. 8. Torque/speed characteristics of the first case.

In this section, three cases of cascading induction motor with DC motor are analyzed as follows:

First case: Cascaded 25 hp (18,650 W) induction motor with 5 hp (3730 W) DC motor and the data of the motors are in Tables 3and 4:

Fig. 8 illustrates the torque/speed characteristic of the 25 hp (18,650 W) induction motor and also the torque/speed characteristic of 5 hp (3730 W) separately excited DC motor. These two motors are connected in cascade and the resultant torque/speed characteristic is compared with one big single induction motor and all are illustrated in Fig. 8.

Several improvements in the torque/speed characteristic of the 30 hp (22,380 W) set (induction motor cascaded with DC motor) are noticed, the starting torque and the maximum torque are significantly increased. Also, the torque for the entire speed range increased due to the cascading process.

Second case: Cascaded three motors together, 15 hp (11,190 W) induction motor with 10 hp (7460 W) induction motor with 5 hp (3730 W) DC motor, the data of the motors are in Tables 5 and 6.

Fig. 9 illustrates the torque/speed characteristic of 15 hp (11,190 W) induction motor, 10 hp (7460 W) induction motor and 5 hp (3730 W) DC motor and the resultant torque of the cascaded

Table 5
Shows data of induction motor of second cascading.

hp	W	V_{L-L}	$2P$	R_1	R'_2	X_1	X_2	X_m	F(Hz)
10	7460	208	4	0.33	0.17	0.42	0.42	16	60
15	11,190	400	4	1.48	0.31	0.18	0.18	24.89	60
30	22,380	400	4	0.73	0.16	0.16	0.16	14.96	60

Table 6
Shows data of the DC motor of second cascading.

hp	W	V_t	R_a	R_F	I_F	K	W_{rated}
5	3730	240	2.581	281	1.06	0.9383	1750

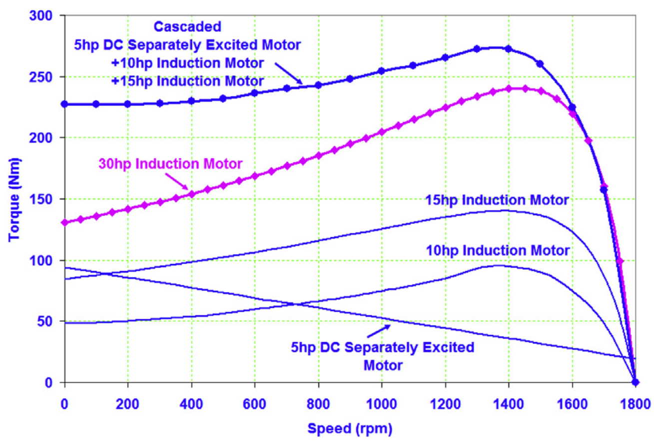

Fig. 9. Torque/speed characteristics of the second case.

Table 7
Data of the induction motor of the third cascading.

hp	W	V_{L-L}	$2P$	R_1	R'_2	X_1	X_2	X_m	F(Hz)
15	11,190	400	4	1.48	0.31	0.18	0.18	24.89	60
30	22,380	400	4	0.73	0.16	0.16	0.16	14.96	60
50	37,300	460	4	0.33	0.17	0.42	0.42	30	60

group is compared with the 30 hp (22,380 W) standalone induction motor.

Here by connecting the separately excited DC machine to the two induction machines, it noticeably affects the starting torque of the group as it seems almost constant all over the speed range.

Table 8
Data of the DC motor of third cascading.

hp	V_t	R_a	R_F	I_F	K	W_{rated}
5	240	2.581	281	1.06	0.9383	1750

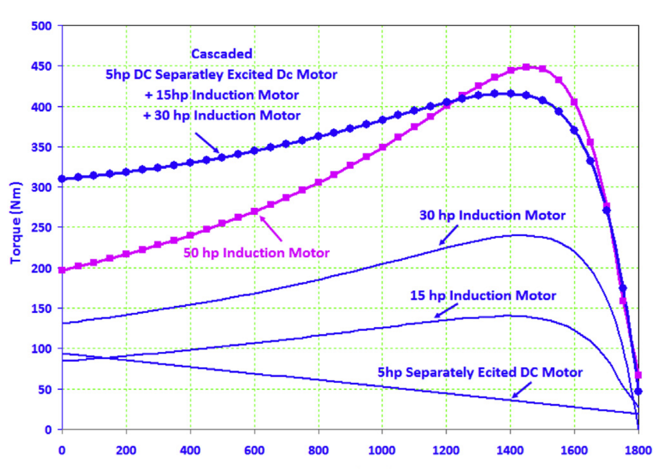

Fig. 10. Shows torque/speed characteristics of the third case.

Third case: Cascaded three motors together, 30 hp (22,380 W) induction motor with 15 hp (11,190 W) induction motor with 5 hp (3730 W) DC motor, the data of the motors are in Tables 7 and 8.

Fig. 10 describes the torque–speed curves of both the set and individual motors. It is clear that the improvement has generally occurred.

6. Conclusion

The paper opens a new era for the electrical machines by introducing more advantages of cascading electrical machines. It also introduces further studies of a new concept relates to the electrical machines and more particularly to the induction motors which is the connection of a small sizes induction motors in cascade instead of one big size induction motor in order to obtain new electromagnetic system that has a better energy conversion process during the balanced and the unbalanced operation. The paper uses a precise method for assessing the performance of the induction machines which are supplied via the unbalanced supply. This method includes the magnitude and angle of the voltage. Different sets of electrical machines, either have the same type or different types, are connected in cascade. The electrodynamic system and the energy conversion both are improved due to the cascading process. The parameters of the cascaded set of the machines are different than one big standalone process that can give higher torque and better torque/speed characteristic. The unbalanced supply and its impact on the electrical machine are a power quality issue. The degree of voltage unbalance is a quantity and this paper assesses it precisely by using the magnitude and angle to asses it. The cascaded group has higher starting and maximum torques. Consequently, it has an efficient energy conversion process during the balanced and the unbalanced operation. Then, the cascaded induction motor with the DC motor provides more advantages from the set which has higher starting torque and maximum torques. Finally, it is recommended that the concept of cascading the electrical machines is better in the energy conversion process and more efficient during both balanced and unbalanced operation.

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