**Performance Evaluation of Different NEMA Induction Motor Designs under the Effect of Unbalanced Supply Voltages**

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**ABSTRACT**

Three-phase induction motors (IMs) are generally used in commercial, industrial, and domestic applications because of their advantages, such as good self-starting ability, simplicity, high reliability, cost-effectiveness, low maintenance, and ruggedness in construction. The IMs are exposed to different internal and external faults; one of the most popular kinds of external faults is unbalanced supply voltages. Unbalanced supply voltage is a popular and worldwide phenomenon that has been found to be very effective in decreasing the characteristics of IMs. In this work, the adverse effect of unbalanced supply voltages on the steady-state characteristics of all NEMA (National Electrical Manufacturers Association) designs of 20hp squirrel cage IMs (SCIMs) is shown. A symmetrical component is used to determine the performance of each NEMA design operating in different unbalanced supply voltage situations. The importance of this paper is that it likens different NEMA designs regarding torque-speed characteristics, efficiency, power factor, stator currents, rotor currents, torque pulsation, ripple in rotor speed, and starting up performances when subjected to over and under unbalanced supply voltage conditions. Further, the MATLAB and Simulink environments have been utilized concurrently for simulation purposes.

*Keywords*: Induction Motors (IMs), NEMA Designs, Under voltage Unbalance (UVU),

Over Voltage Unbalance (OVU), Voltage Unbalance Factor (VUF).

**Highlights**

-Performance analysis of different NEMA designs of IMs under unbalanced supply voltage.

-Investigation the effect of different unbalanced voltage magnitudes for similar VUF with OVU and UVU on different NEMA designs.

- The MATLAB Software used for simulation purpose.

**تقييم أداء تصاميم الجمعية الوطنية لمصنعي الأجهزة الكهربائية لمختلف أنواع المحركات الحثية تحت تأثير الجهد غير المتوازن**

**الخلاصة**

تُستخدم المحركات الحثية ثلاثية الطوربشكل عام في التطبيقات التجارية والصناعية والمنزلية نظرًا لمزاياها، مثل القابلية الجيدة على البدء الذاتي، والبساطة، والوثوقية العالية، و التكلفة الاقتصادية، وانخفاض الصيانة، والمتانة في التركيب. تتعرض المحركات الحثية لأعطال داخلية وخارجية مختلفة؛ أحد أكثر أنواع الأعطال الخارجية شيوعًا هو الجهد غير المتوازن. يعد الجهد غير المتوازن ظاهرة شائعة وعالمية وقد ثبت أنها فعالة جدًا في تقليل خصائص المحركات الحثية. في هذه الدراسة، يتم عرض التأثير السلبي للجهود غير المتوازنة على خصائص الحالة المستقرة لجميع تصاميم الجمعية الوطنية لمصنعي الاجهزة الكهربائية للمحرك الحثي ذي القفص السنجابي بقدرة 20 حصانا. يتم استخدام المركبات المتماثلة لتحديد أداء كل تصميم من التصاميم التي تعمل في حالات مختلفة من الجهد غير المتوازن. تكمن أهمية هذه االدراسة في أنها تشبه تصميمات الجمعية الوطنية لمصنعي الاجهزة الكهربائية المختلفة فيما يتعلق بخصائص السرعة-العزم، والكفاءة، ومعامل القدرة، وتيارات الجزء الثابت، وتيارات الجزء الدوار، ونبض عزم الدوران، والتذبذب في سرعة الدوار، وأداء بدء التشغيل عند التعرض لظروف جهد غير متوازن زائد أو منخقض، علاوة على ذلك، تم استخدام برامج MATLAB وSimulink بشكل متزامن لأغراض المحاكاة.

**الكلمات الدالة**: المحركات الحثية، تصاميم الجمعية الوطنية لمصنعي الاجهزة الكهربائية، الجهد غير المتوازن المنخقض، الجهد غير المتوازن الزائد، معامل عدم توازن الجهد.

**1.INTRODUCTION**

In general, a three phase IMs are used in industry applications because of their good features in addition to high reliability and robustness [1] . IMs that potentially establish emphasized condition under which their performance are unfavorably affected, are seen in numerous applications [2]. The squirrel cage induction motor (SCIM), in addition to its benefits, has a low beginning torque. The use of SCIMs in some applications that require high beginning torque has been limited. As a result, by modifying the reactance and resistance of the rotor through the shape of the rotor slots and rotor bars of SCIMs, it is possible to improve the beginning and regular running performance. The NEMA criterion mostly defines four design classes for SCIMs: Design A, design B, design C, and design D [3]. These classes are distinguished by the shape of rotor slots, bar materials and torque-speed performances.

The exact balanced supply voltage can never be maintained due to load variation, and an unbalanced voltage can cause severe troubles which lead to many induction motor's unseasonable failure. Since the last three centuries, many researchers have been interested in studying the effect of an unbalanced supply voltage on three-phase IM performance [4]. Generally, electrical motors are designed to work with balanced and pure sinusoidal supply voltages. In [5], a complete symmetrical component mathematical model for determining the output power of the IM that works under unbalanced voltages, considering corresponding angles and neglecting constant losses, has been proposed.

The authors in [6, 7] have examined the harmful effects of unbalanced supply voltage on IMs properties. They have found that the current unbalance factor (CUF) is 6–10 times higher than the voltage unbalance factor (VUF). The performance of three-phase IMs has been simulated using the finite element method under unbalanced supply voltage conditions [8].

A complete investigation of the impact of positive and negative voltage portions as well as the angle between them on motor performance has been presented [4]. In [9], the behavior and efficiency of two dissimilar kinds of IMs that are coupled and work with balanced and imbalanced supply voltages have been presented. The effects of the positive sequence voltage component part on IMs losses, developed torque, and the sensibility of motor variables have been investigated by [10].

A new definition of phase imbalance index is proposed by [10, 11] for different scenarios with presenting a simple comparing of voltage supply quality in terms of phase angle, which regards the normal 1200 displacement of a three-phase supply. The operational data of three-phase IM running subjected to balanced and unbalanced voltage supplies has been simulated using data mining [12]. The effects of voltage unbalance and harmonic distortions on different efficiency IM classes behavior were investigated [13, 14]. They deduced that the losses due to voltage unbalance and harmonic distortion of the IM are greater in the higher efficiency classes of the IM.

A complete mathematical model of static rotor resistance chopper speed control of slipring IMs subjected to imbalanced supply voltage at different duty cycles has been proposed and discussed by [15]. A mathematical model for predicting the behavior of slip energy recovery under unbalanced supply voltage at different inverter firing angles has been proposed in [16].

In [17, 18], a simulation model using MATLAB/Simulink for analyzing the steady state performance of the three phase IM under different unbalanced supply voltage conditions has been proposed. The performance of a three-phase induction motor subjected to the operation of single-phasing effects in steady-state conditions under different supply voltage unbalances is presented in [19]. A regular analysis of the effects of voltage unbalance and harmonic distortion onto the drive systems of IMs was presented by [20]. It was found that the voltage unbalance has a larger effect on the developed torque than the harmonic effects.

The impact of non-sinusoidal supply voltage on the steady-state characteristics of NEMA designs of SCIMs related to the skin effect has been investigated in [21]. [22] has concluded that vibrations caused by voltage imbalance are notably more prominent in larger efficiency IMs as compared to standard efficiency IMs.

There have been reported in the literature a lot of studied on decreasing losses and increasing the efficiency of IMs regarding voltage unbalance; for example, the improvement of the IM efficiency can be attained by modifications in stator and rotor design and their parameters, simultaneously considering the quality of the supply voltage.

Based on the previous discussion, this paper investigates the steady-state characteristics of NEMA designs A, design B, design C and design D of SCIMs under the effect of an unbalanced supply voltage. The symmetrical component technique and mathematical equations related to IMs equivalent model are presented. Furthermore, this paper studies the effect of different unbalanced voltage magnitudes for similar VUF with OVU and UVU on the developed electromagnetic torque, stator current, rotor current, torque pulsation, speed fluctuation, power factor, and efficiency. The remaining sections of the paper are as follows: Section two discusses the research method and modeling of SCIM under an unbalanced supply voltage. Section three presents the results and discussion, and the last section is the conclusion.

**2.** **THE RESEARCH METHODOLOGY**

In typical electrical power distribution system analysis, a balanced state is assumed. Voltage unbalance is a voltage disturbance in the positive sequence induced by the negative and zero-sequence voltage components. The zero-sequence component is zero since the IMs are connected in mesh or wye connections without neutral. Therefore, voltage imbalance is mainly caused by the negative sequence components [23], correspondingly, the voltage imbalance is the emplacement of negative sequence voltage over positive sequence voltage. Whenever the positive sequence voltage component is disrupted and its value gets smaller than the rated value, this phenomenon is under voltage, whereas for more than the rated value, the state is over rated voltage.

The steady-state analysis of 3-phase IMs operating under an unbalanced supply voltage is traditionally conveyed by applying the symmetrical component technique, using the positive and negative sequence equivalent models of IMs. Fig. 1. displays the per phase equivalent circuit of designs A, B, and D of IMs.



**Fig. 1.** Per-phase Equivalent Circuit for designs A, B, and D.

Where is the applied motor phase voltage, is the stator phase current, and are stator resistance and reactance per phase, respectively, is the rotor referred current, and are the referred rotor resistance and reactance, respectively, and is the magnetizing reactance.

The input impedance for the positive sequence model and the negative sequence impedance may be determined from Fig. 1, where i = 1 for the positive sequence and i = 2 for the negative sequence.

The operating slip (),

Where ns is the synchronous speed of IMs and n is the rotor speed. The negative sequence slip (),

The input impedance,

Using the method of mesh analysis, we obtain the matrix equations as,

Where , =,

Inverting Eq. (4) to determine the stator and rotor currents,

Determining the motor performance requires the positive and negative sequences of stator and rotor currents, which can be calculated by the Fortescue matrix transformation as shown in Eqs. (6-9),

Where a=exp(j2π/3) is the Fortescue operator, and the voltage unbalance factor (VUF) defined by the IEC [23, 24] is,

The stator current unbalance factor (CUFs) and rotor current unbalance factor (*CUFr*) is given by Eqs. (10, 11);

The total input active and reactive power into the motor is given by,

The input power factor can be determined with,

The negative sequence portion of an unbalanced supply voltage develops an air-gap rotating magnetic field against the direction of the rotor, and this produces an undesirable negative sequence component. As a result, torque pulsation, speed reduction, more losses, and derating of the motor are caused. Furthermore, because of the low value of the impedance of the negative sequence circuit, a high negative sequence current increases motor loss and decreases motor life.

The electromagnetic torque developed by the IMs under an unbalanced supply voltage, is the resultant torque developed by the positive sequence component and negative sequence component of the rotor currents, which is given by

The motor efficiency can be given by,

The performance analysis of design C (double cage IM) can be investigated depending on the equivalent circuit, as shown Fig. 2.

  
**Fig. 2**. Per-phase Equivalent Circuit for design C (double cage).

The mesh equation for this model,

Where and

The determent of Eq. (17) is given by,

The stator current can be calculated,

Where

The input power and the power factor can be calculated by Eqs. (12-14). The electromagnetic torque developed by the IM under unbalanced supply voltage conditions is the resultant torque developed by the positive sequence component and negative sequence component of the outer cage rotor current and inner cage rotor current, which is given by Eq. (23),

The impact of an unbalanced supply voltage on the electromagnetic torque developed can be analyzed by using the torque ripple factor (TRF), and can be calculate,

Where and are peak-to-peak and average developed torque, respectively.

**3.THE RESULTS AND DISCUSSION**

The harmful impact of the unbalanced supply voltage on the characteristics of NEMA design A, design B, design C, and design D with the same rating of wye-connected, 20 hp, 400 V, 50 Hz, two-poles has been examined, and the parameters are given in Table 1 . The four designs IMs have been examined with unbalanced supply voltage as a function of VUF, which is allowed to vary between (0 - 7) % to exceed the NEMA recommended limit (5%) for over and under voltage supply as shown in Table 2, so as to investigate which designs have been mainly affected. The phase A is adjusted to 231, and the two remaining phases B and C are adapted to obtain the required VUF% by changing the value and the angle of phase C and comparing with the same VUF for UVU and OVU conditions. The MATLAB/Simulink, as shown in Fig. 3, is implemented to examine the performance of different NEMA design models under different unbalanced voltage levels, such as the electromagnetic torque response, the rotor speed response, ripple in speed, and torque pulsation.

**Table 1** The motor parameters of all NEMA designs [25]

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Design | A | B | C | D |
| RS(Ω) | 0.1456 | 0.1456 | 0.1456 | 0.1456 |
| Rr/(Ω) | 0.3267 | 0.46961 | 0.684(inn. cage)  2.521(out. cage) | 1.36 |
| XS(Ω) | 0.7681 | 0.7681 | 0.7681 | 0.7681 |
| Xr/(Ω | 0.7681 | 1.1772 | 1.822(inn. cage)  0.582(out. cage) | 0.7681 |
| Xm(Ω) | 33.3 | 33.3 | 33.5 | 33.3 |

**Table 2** The supply voltages, positive sequence supply voltage component, negative sequence supply voltage component, and VUF% supplied to each NEMA designs

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| VUF% | Case | Va(V) | Vb(V) | Vc(V) | Vp(V) | Vn(V) |
| 0 | Bal. | 231 | 231 | 231 | 231 | 0 |
| 1 | UVU | 231 | 228.84 | 226.8 | 228.81 | 2.32 |
| 3 | 231 | 225 | 218.9 | 224.91 | 6.88 |
| 5 | 231 | 221.84 | 211.6 | 221.3 |  |
| 7 | 231 | 218.55 |  | 217.48 | 15.33 |
| 1 | OVU | 231 | 233 | 235.05 | 233.1 |  |
| 3 | 231 | 236.88 | 243.6 | 237.1 |  |
| 5 | 231 | 240.5 |  | 240.9 |  |
| 7 | 231 | 245 | 256.2 | 243.6 |  |

**Fig. 3.** The SIMULINK Model of Three-phase IM under different unbalanced supply voltage.

1. The Effect of Unbalanced Supply Voltage on the Torque - Speed Characteristics

The torque-speed characteristics for all NEMA design IMs under different unbalanced supply voltage conditions are shown in Fig. 4. Which shows the change of electromagnetic torque developed with motor speed in various values of VUF from (0-7) % in the range of UVU and OVU. It can be noted that with decreasing VUF from (7% of OVU) to (7% of UVU) the rotor speed decreases.

**Fig. 4.** Torque slip performance of all NEMA designs for various unbalance supply voltage conditions.

Table 3 displays the variation of motor speed, starting torque, and pullout torque for each NEMA design at full load under varying voltage unbalance conditions. It can be seen that with increasing the VUF for OVU, the rotor speed is increased by 12 rpm (design A), 19 rpm (design B), 20 rpm (design C), and 49 rpm (design D), while the rotor speed is decreased with UVU by 14 rpm (design A), 22 rpm (design B), 28 rpm (design C), and 66 rpm (design D). Design D is more affected than the other designs. Further, in the same table, it can be noted that the increasing or decreasing of starting torque with UVU and OVU is more affected by this phenomenon in design D, whereas the starting torque increases by (17.3 Nm) for OVU and decreases by (16.6 Nm) with UVU in design D, while for design B it increased by (6.54 Nm with OVU) and decreased by (6.26 Nm with UVU). In addition, it can be shown that the increasing or decreasing of maximum torque with UVU and OVU in designs A and B is more affected by VUF, whereas the maximum torque increases by 18.2 Nm for OVU and decreases by 16.4 Nm with UVU in design A, while for design B it increased by (14.3 Nm with OVU) and decreased by (12.9 Nm with UVU.

The simulation response results for design A, design B, design C, and design D are observed in Table 4 for settling time (Ts) and rising time (Tr) with VUF% for different voltage unbalanced conditions. It should be noticed that for all designs with increasing VUF, the Ts and Tr are reduced for OVU, and increased for UVU voltage unbalance conditions.

The simulation response results for design A, design B, design C, and design D are observed in Table 4 for settling time (Ts) and rising time (Tr) with VUF% for different voltage unbalanced conditions. It should be noticed that for all designs with increasing VUF, the Ts and Tr are reduced for OVU, and increased for UVU voltage unbalance conditions. Further research reveals that NEMA design B has the lowest torque pulsation and rotor speed ripples, whereas NEMA design C has the fewest Ts and Tr.

**Table** 3 The variations of motor speed, starting torque, and pullout torque against VUF% for various NEMA Designs

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| VUF% | Case | Rotor Speed (rpm) | | | | Starting Torque (Nm) | | | | Pullout Torque (Nm) | | | |
| Design A | Design B | Design C | Design D | Design A | Design B | Design C | Design D | Design A | Design B | Design C | Design D |
| 7 | OVU | 2906 | 2868 | 2841 | 2606 | 70.7 | 61.5 | 126.1 | 163.1 | 165.3 | 130.7 | 133.7 | 163.9 |
| 5 | 2903 | 2860 | 2837 | 2598 | 68.7 | 59.7 | 122.3 | 158.2 | 160 | 126.5 | 129.7 | 158.9 |
| 3 | 2900 | 2853 | 2831 | 2581 | 66.3 | 57.7 | 118.2 | 152.9 | 154.4 | 122.1 | 125.3 | 153.6 |
| 1 | 2896 | 2848 | 2825 | 2566 | 64.2 | 55.9 | 114.6 | 148.2 | 149.6 | 118.3 | 121.4 | 148.8 |
| 0 |  | 2894 | 2845 | 2821 | 2559 | 63.2 | 55 | 112.7 | 145.8 | 147.1 | 116.3 | 119.4 | 146.4 |
| 1 | UVU | 2892 | 2842 | 2816 | 2553 | 62.2 | 54.02 | 110.7 | 143.2 | 144.6 | 114.3 | 117.4 | 143.9 |
| 3 | 2888 | 2838 | 2810 | 2536 | 60 | 52.17 | 106.9 | 138.3 | 139.6 | 110.4 | 113.3 | 138.8 |
| 5 | 2884 | 2834 | 2802 | 2516 | 58.0 | 50.44 | 103.3 | 233.7 | 135.1 | 106.8 | 109.5 | 134.2 |
| 7 | 2880 | 2829 | 2793 | 2493 | 56 | 48.74 | 99.88 | 129.2 | 130.7 | 103.4 | 105.8 | 129.7 |

Fig. 5 shows the linear characteristics between torque ratio factor TRF% and VUF for OVU and UVU supply voltage conditions. It can be seen that design A and design C have the larger TRF% and torque pulsation if compared with design D and design B. On the other hand, Fig. 6 shows the rotor speed ripple versus VUF% for different NEMA designs. It is shown that design A has a maximum speed ripple at VUF of 7% and a minimum at balanced supply voltage. In addition, it can be determined that the effect of OVU on the torque pulsation and rotor speed ripple for the same VUF% is greater as compared to UVU voltage conditions.

**Table 4** The change of settling and rising times for various NEMA designs as a function of VUF%

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | Over Voltage | | | | Balance | Under Voltage | | | |
|  | VUF% | 7 | 5 | 3 | 1 | 0 | 1 | 3 | 5 | 7 |
| Design  A | Ts(msec) | 603 | 645 | 680 | 748 | 845 | 896 | 935 | 1038 | 1200 |
| Tr(msec) | 276 | 296 | 311 | 328 | 340 | 361 | 387 | 413 | 430 |
| Design  B | Ts(msec) | 780 | 875 | 931 | 1016 | 1110 | 1240 | 1430 | 1681 | 2200 |
| Tr(msec) | 350 | 370 | 395 | 424 | 440 | 465 | 515 | 562 | 610 |
| Design  C | Ts(msec) | 320 | 331 | 345 | 375 | 400 | 421 | 428 | 448 | 480 |
| Tr(msec) | 207 | 221 | 232 | 246 | 253 | 264 | 270 | 279 | 290 |
| Design  D | Ts(msec) | 421 | 436 | 460 | 486 | 500 | 519 | 538 | 576 | 610 |
| Tr(msec) | 215 | 223 | 231 | 235 | 240 | 250 | 266 | 282 | 295 |

**Fig. 5**.TRF against VUF for all NEMA designs for various unbalance supply voltage.

**Fig. 6**. Rotor speed ripple against VUF for all NEMA designs for various unbalance supply voltage conditions

Figures 7, 8, and 9 show the electromagnetic torque developed response at balanced supply voltage (VUF = 0%), under voltage supply (VUF = 7%), and over voltage supply (VUF = 7%) for all NEMA design of IMs, respectively. It can be seen that the time that is required to reach the steady-state full load torque in design B is greater than in other three designs. This is due to a high electrical time constant because the ratio of rotor inductance to rotor resistance is higher than in designs A, C, and D, for the same mechanical time constant. At the same time, it is less effective in designs C and D, and the torque pulsation will increase with increasing VUF. Overvoltage unbalance causes more torque pulsation in comparison with undervoltage unbalance as shown in Fig. 5.

Figures 10, 11, and 12 show the rotor speed response at balanced supply voltage (VUF = 0%), under voltage supply (VUF = 7%), and over voltage supply (VUF = 7%) for all NEMA design IMs, respectively. It can be seen that the time needed to attain the steady-state full load speed in design B is greater than in the other three NEMA designs. The rotor speed ripple at balance supply is about 0.1 rpm for all NEMA designs, but with increasing VUF, the rotor speed ripple will increase in different proportions to about 12 rpm for UVU and to 15 rpm for OVU for design A, as shown in Fig. 5.

**Fig. 7** The electromagnetic torque starting response at full load and balanced supply voltage for different NEMA Design IMs

**Fig.8** The electromagnetic torque starting response at full load and under voltage unbalance UVU) supply (VUF=7%) for different NEMA Design IMs

**Fig.9** The electromagnetic torque starting response at full load and over voltage unbalance (OVU) supply (VUF=7%) for different NEMA Design IMs

**Fig.10** The rotor speed response at full load and balanced supply voltage for different NEMA Design IMs

**Fig.11** The rotor speed response at full load and under voltage unbalance(UVU) supply (VUF=7%) for different NEMA Design IMs

**Fig.12** The rotor speed response at full load and over voltage unbalance (OVU) supply (VUF=7%) for different NEMA Design IMs

1. The Effect of Supply Voltage Unbalance on the Stator and Rotor Currents

The positive-sequence component, negative-sequence component, and CUF for stator and rotor phase currents are given in Fig. 13 and Fig. 14, respectively. It is shown that the stator negative-sequence component current for design A increases from (0-12.1) A for OVU and (0-10.05) A for UVU, whereas the stator positive-sequence component current decreases from (27.5 to 26) A for OVU and increases from (27.5 to 29.1) A with UVU for design A. It can be noted that the rotor negative-sequence component current for design A increases from (0-11.62) A for OVU and (0-9.68) A for UVU, whereas the rotor positive-sequence current decreases from (26.12 to 24.53) A for OVU and from (26.12 to 27.83) A for UVU.

The CUF of the stator for design A, which is the largest, varies from 45.8% (OVU) to 33.1% (UVU), besides, for design B, which has the minimum variation, it varies from 35.1% (OVU) to 25.7% (UVU). The CUF of rotor current for design A, which is the largest, varies from 47.3% (OVU) to 34.8% (UVU); besides, for design B, which has the minimum variation, it varies from 36.65% (OVU) to 26.68% (UVU). It concludes that the CUF of stator and rotor currents of NEMA design A has a larger value than that of design B, which has a lower value in both OVU and UVU supply voltage conditions.

Fig. 15 displays the changing of positive and negative-sequence impedance against of VUF for UVU and OVU for different NEMA designs. It can be noted that all positive sequence impedances are slightly decreased (for OVU) or increased (for UVU) with changing VUF, while the negative-sequence impedance does not rise and fall notably with VUF.

**Fig. 13**. Negative, positive, and CUF% of stator currents against VUF%.

**Fig. 14**. Negative, positive, and CUF% of rotor currents against VUF%.

**Fig. 15**. The positive, and negative-sequence impedances versus VUF% for different NEMA deigns.

C. The Effect of Supply Voltage Unbalance on Power Factor and Efficiency

The variation of different NEMA design power factors against VUF for OVU and UVU unbalanced supply voltage conditions is shown in Fig. 16. It is clear that by increasing the VUF in the OVU and UVU regions, the power factor decreases. It is observed that the power factor slightly raises for VUF (0–3) % in UVU due to decreasing phase B and phase C voltages and then its magnetizing current, while for OVU it still decreases because of increasing the magnetizing current due to increasing phase B and phase C phase voltages. Further, the power factor of designs A and B is less than that of designs C and D.

Fig. 17 presents the motor efficiency versus VUF for UVU and OVU. As the asymmetry of the supply voltage increases for OVU and UVU, the efficiency decreases. The efficiency decreases with increasing voltage unbalance, especially in the OVU region, because the negative sequence current (copper losses) effect is greater than the rate of increase in power factor. As a result, efficiency has decreased.

It can be noted that the efficiency of all NEMA designs decreases with the VUF for OVU more than with the same VUF for UVU. The efficiency of design A at zero VUF is 89.5%, and when VUF% is 7 (OVU), the efficiency is 87.5%, while for the same VUF%, the efficiency is 88.3% with UVU.

**Fig. 16**. The variation of power factor with VUF for different NEMA designs.

**Fig. 17**. The variation of efficiency with VUF for different NEMA designs.

**4.CONCLUSION**

Globally, a reduction in energy waste due to voltage unbalance will help in saving some millions of dollars paid out annually on unusable energy wasted largely as heat. This paper presents the analysis of the steady-state performance for different NEMA design of IMs under the impact of unbalanced supply voltage, in combination with over voltage and under voltage unbalance conditions. It can be seen that the sensitivity of all NEMA designs of IMs to unbalanced supply voltage is different according to the obtained results. The following conclusions can be drawn based on the present paper:

Th positive and negative equivalent circuit models were presented and their effects on the net torque-speed characteristics were described. The negative sequence portion of torque decreases the starting torque, pull out torque, and speed at the rated load. The NEMA design D of IM has larger starting and pull out torque than other designs.

The startup time in case of under unbalanced supply voltage conditions is larger than that of over voltage unbalanced supply conditions, in contrast, the torque pulsation, and rotor speed ripple in case of over voltage unbalance is more than that of under voltage unbalance conditions for all NEMA designs of IM.

The values of rotor speed ripple and torque pulsation increase with increasing VUF under unbalanced supply voltage conditions. It can be noted that NEMA design A has the maximum deviation in ripples for rotor speed (15 rpm) and percentage torque ripple factor (95%), while NEMA design B has a smaller variation in rotor speed variation (12 rpm) and percentage ripple factor of 72% compared with other designs.

For the same VUF, the power factor drops with increasing positive sequence voltage (OVU) rather than the negative sequence voltage component due to stator magnetic core saturation, which causes decreasing magnetizing reactance and increasing magnetizing current. As a result, more reactive power has been drawn.

Both positive and negative sequence voltage components have an effect on motor efficiency, and in design A, the efficiency decreases (from 89.5 % to 8.5%) with increasing the VUF (0-7)%, and it decreases ( from 89.5% to 88.2%) for under voltage unbalanced supply conditions.

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1. [↑](#endnote-ref-1)