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Single Phasing Effects on the Behavior of Three-Phase Induction Motor

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Abstract: The output of three-phase induction motors (3IM) is adversely affected by voltage imbalance. This work analyzes and estimates the output of a 3PIM operating on a balanced supply while contrasting it with a "single phasing" case. Simulation additionally makes use of MATLAB /SIMULINK. The effects of single phasing on a 3PIM's performance for system rerating are suggested. An example was given using a 4 kW 3PIM. It is not a big problem; however, it should be considered if a three-phase motor is purposely connected to a single-phase source or whenever a three-phase source loses one of its phases due to a fault. When a three-phase motor operates in a single-phase, the motor will continue to try to run the load until it is destroyed or the protective components remove the motor from the line. The outcome of single phasing is an increase in phase currents, which causes overheating and damage to the motor. A downline on the distribution grid or a blown pole upper fuse might cause a phase loss on a three-phase line. A single-phase overload condition that causes one fuse to blow or a device breakdown inside the end-user facility may also result in a single-phase loss.

تأثير فقدان واحد من الأطوار على سلوك المحرك الحثي ثلاثي الأطوار

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الخلاصة

يعد عدم توازن الجهد ظاهرة عالمية لها تأثير سلبي على خرج المحرك الحثي ثلاثي الطور. يهدف هذا العمل إلى فحص وتقدير ناتج محرك حثي ثلاثي الأطوار يعمل على مصدر متوازن ومقارنته بحالة "الطور الأحادي". استخدم برنامج MATLAB / SIMULINK في المحاكاة. ايضا تم اقتراح تأثيرات الطور الفردي على أداء المحرك الحثي ثلاثي الطور لإعادة تحويل النظام. على سبيل المثال ، تم اختيار محرك حثي ثلاثي الطور بقدرة 4 كيلو واط. يمكن فحص حالة التشغيل المتوازنة مع مرحلة واحدة ، ولكن يجب ألاخذ في الاعتبار بعد فقدان طور واحد من مصدر ثلاثي الطور أثناء حالة حدوث عطل ، أو في أي وقت يتم اختياره عن قصد لتوصيل المحرك بمصدر أحادي الطور. عندما يكون المحرك ثلاثي الطور في حالة أحادي الطور ، فقد يحاول إنتاج الحد الأقصى من القدرة الحصانية اللازمة لتلبية المتطلبات. سيستمر المحرك في محاولة تشغيل الحمل حتى يتلف أو تقوم مكونات الحماية بإخراج المحرك من الخط. نتيجة الطور الفردي هي زيادة في التيارات الطورية ، مما يؤدي إلى ارتفاع درجة الحرارة ويضر بالمحرك. قد يتسبب الخط السفلي على شبكة التوزيع أو الصمام العلوي في فقدان طورواحد على خط ثلاثي الطور. ايضا تتسبب حالة الحمل الزائد أحادي الطور التي تسمح لمنصهر بالانفجار أو عطل في الجهازللمستخدم النهائي في حالة حدوث فقدان احد الاطوار.

الكلمات الدالة: المحركات الحثية ، الطور الأحادي ، عدم توازن الجهد ، عزم الدوران ، التسلسل السلبي ، التسلسل الإيجابي.

1.INTRODUCTION

Many undesirable impacts are caused by a 3PIM with imbalanced voltages. These impacts include higher losses and, as a result, a temperature rise, reduction in efficiency, torque, and motor insulation life. This is known as "single phasing." Many studies have considered the impact of imbalanced supply voltage on the performance of 3PIM. A new factor of unbalance and the complex voltage unbalance factor (CVUF) can be applied for the exact analysis of the IM performance under unbalanced supply voltage conditions. Additional emphasis is placed on the (CVUF) angle to determine the precise derating factor value. Also, a special emphasis is placed on the effect of the (CVUF) angle on the IM performance [1]. Silva, 2022 employed a negative sequence component in replacement to the voltage unbalance factor (VUF) to investigate the effect of unbalance. Variations in the voltage unbalance definition were also investigated [2]. Gnaciński and Klimczak investigated the thermal exhibiting of the genuine rated power of 5.6 MW and four motors of the rated power of 200 kW motors. Two critical findings were made. For starters, voltage sub-harmonics significantly impacted motor thermal degradation. Second, they considered the total cost of motor failure owing to harmonic contamination and voltage imbalance [3]. Faiz et al. (2004) investigated the unfavorable impacts of a separable unbalanced voltage on an IM performance, suggesting that the present definitions of unbalanced voltages are not broad and thorough. As a result, the results of these motor performance studies are not very reliable. It is demonstrated that a more precise imbalanced factor must be defined to obtain more precise findings. The theoretical analysis was supported by experimental results [4]. Kersting (2005) examined three modes of operation of IMs with a single phasing condition. According to the results, the total losses of the motor rose dramatically from 9.4kW under normal operating circumstances to 98.2kW during single phasing. An excessive loss would nearly always result in motor heating, and the requirement to prevent motors from single phasing was well documented [5]. A statistical method established several multiple regression types to evaluate the effect of unbalance voltage on the efficiency and power factor of IMs with the digitally controlled pole. The equations are associated with the positive and negative sequences voltage [6]. Sutherland (2006) discussed the effects of reclosing IM and other industrial loads. The heating effects and various protection relay characteristics were provided to respond to unbalanced currents [7]. Raj et al. (2006) studied the supply voltage distortion in the non-sinusoidal form leading to unsafe harmonics creation, which exchanged the performance of the motor, producing a pulsating torque and noise [8]. Anwari (2010) examined the IM's performance using the MATLAB program. According to the simulation results, the International Electrotechnical Commission's definition of voltage imbalance shared with the coefficient of an unbalanced situation can be used to precisely estimate the total copper losses, input power, power factor, and total output torque [9]. Jayatunga et al. (2012) examined the IM loading level impact on the joining voltage imbalanced production point. According to the presumptive Simulink design, hardly loaded IMs had worse negative sequence voltage unbalance factor (VUF) at the point of joining [10]. Pesquer et al. (2012) classified voltage imbalances to study the various rates and types of voltage unbalance; besides, the impacts it had on torque and current, and the implications of such effects [11]. Singh et al. (2012) offered a cutting-edge phase angle algorithm for calculating voltage imbalance factor (VUF) from line voltages, supported by test findings. The findings demonstrated that the positive sequence voltage must be considered to assess unbalanced voltages accurately [12]. Agamloh et al. (2014) experimentally studied the performance of IMs subjected to single-phasing on the primary side of the distribution transformer that supplied the motors. While single-phasing induced by, say, a blown fuse or a faulty contact was permanently caused by recloser action was temporary [13]. Patil and Chaudhari (2015) discussed the detrimental effects of unbalanced voltage on the 3 hp IM performance variables, such as efficiency, current, speed, temperature increase, torque, and other variables. These effects were supported by the findings of MATLAB simulations, which showed that unbalanced voltages at motor terminals resulted in phase current imbalances 6 to 10 times greater than the voltage unbalance percentage. Since efficiency drastically decreased over 1% of the voltage imbalance, a motor must be derated to function properly [14]. Rahman et al. (2016) concluded that the simulation test demonstrated the total inverter loss value compared to the microgrid system's single-phase inverter. According to their expectations, the three-phase inverter was appropriate for situations where it was economically feasible for the AC voltage at the output to be larger than the DC voltage at the input [15]. Uma and Vijayarekha (2017) used a synchronous IM reference frame equation, VSI switching device model, and diode-bridge-rectifying model to build the Adjusted Speed Drive Mathematical Model (ASD) and evaluate simulated results for the proposed mathematical model [16]. Aderibigbe et al. (2017) studied, utilizing phase frame analysis, the performance of a 3φIM under unbalanced voltage settings. The findings of this investigation showed that supplied imbalance detrimentally impacted the 3φIM performance [17]. Quispe et al. (2018) thoroughly examined the impact of positive and negative sequence voltage components and the angle between them on various variables, such as losses, line currents, efficiency, and power factor under various voltage unbalanced situations. A 3φIM with a power rating of 3 HP was used as a case study. According to the study's findings, the positive sequence voltage must be evaluated concurrently with the voltage imbalance factor (VUF) [18]. Nurhaida et al. (2019) studied a three-phase voltage source inverter (VSI) design and its implementation for variable frequency driving. The main goal was the variable frequency output production suitable for supply to the IM for the drive of variable speed control [19]. Singh et al. (2019) explained the steady-state analytical approach in detail and examined and compared the definitions of the voltage imbalance factor from different sources. They proposed mitigation methods for its impacts on the motor [20]. Adekitan (2020) considered a fresh definition of phase imbalance that considered the three phases of the supply's typical 120° rotation. Four operational supply case studies for a 3PIM were used to compare different definitions [21]. Abdulsatar et al. (2021) employed simulation findings to demonstrate the detrimental effects of unbalanced non-sinusoidal voltages that are more than the case of balanced non-sinusoidal voltages. In addition, the computation of voltage imbalance factor (VUF) based on positive and negative sequence components was considered [22]. Abdulsatar et al. (2021) investigated the detrimental effects of an unbalanced 10 hp 3φIM squirrel cage supplied by a three-phase IGBT inverter at full load. MATLAB/Simulink was used to develop and simulate the driving system. A pulse controller that used two pulse width modulation (PWM) levels controlled the inverter switches [23].

The contribution of this work, i.e., Single phasing effects on the behavior of a 3φIM", is to analyze the effects of single-phasing on the performance of an IM in its steady state condition at different supply voltage unbalance. Several factors that impact the motor current imbalance factor, motor current distortion, motor speed, and motor efficiency are discussed. It includes discovering the consequences that may be expected and the magnitude of these effects. Because uneven supply voltage and distortion are predicted to have different effects on the motor, their effects will be evaluated separately. In this research, MATLAB software was used to model and simulate a 3φIM to assess and investigate the machine's behavior subjected to single-phasing. It is meant to concentrate on motor efficiency, generated torque, and other essential aspects that generally influence motor performance.

The organization of this paper is as follows: section one introduces a literature review, and section two contains a mathematical model consisting of IM under single phasing conditions, an open phase model, and equivalent circuit analysis. In section three, the simulation results are presented. Finally, in section four, the key conclusions are reported.

2. THREE-PHASE INDUCTION MOTOR ANALYSIS

2.1 IM Under Single Phasing Condition

In an extreme case of uneven running, single phasing may be considered. It is not a serious issue; however, it should be considered if one phase of a three-phase source fails during a failure situation or if a 3PIM is intentionally connected to a single-phase source. This is known as "single phasing." When a three-phase motor works in the single-phase condition, it might strive to generate the maximum horsepower necessary to meet the demand. The motor will continue to try to run the load until it is damaged or the protecting components relocate the motor out of the line. Single phasing increases phase currents causing overheating, which destroys the motor [24]. A downline on the distribution grid or a burst pole upper fuse might cause a phase loss on a three-phase line. A single-phase overload scenario that permits one fuse to rupture or device breakdown inside the end customer's plant might cause a single-phase loss.

2.2 Open Phase Model

IM under open-phase case in the symmetrical component sequence is explained in Figure 1, which shows the state of the open phase for which "phase a" opens [5].

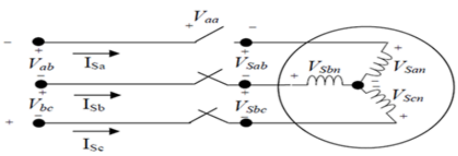

Fig.1 . IM under Open-Phase Case

Where

V_{ab}, V_{bc}, and V_{ca} are the system line-to-line voltages.

V_{Sab}, V_{Sbc}, and V_{Sca} are the working line-to-line voltage at the motor terminal.

V_{San}, V_{Sbn}, and V_{Scn} are the stator line-to-neutral voltages.

I_{Sa}, I_{Sb}, and I_{Sc} are the line currents.

For this operating condition, the line currents must satisfy the following:

$I_{Sa}=0$, $I_{Sc}=-I_{Sb}$

Thus, the currents for "symmetrical component sequence" are:

$$\begin{bmatrix} I_{So} \\ I_{Sp} \\ I_{Sn} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} 0 \\ I_{Sb} \\ -I_{Sb} \end{bmatrix} = \begin{bmatrix} 0 \\ (a-a^2).I_{Sb} \\ (a^2-a).I_{Sb} \end{bmatrix} = \begin{bmatrix} 0 \\ j\sqrt{3}..I_{Sb} \\ -j\sqrt{3}..I_{Sb} \end{bmatrix} \quad (1)$$

From Eq. (1), it is observed that

$$I_{Sn} = -I_{Sp}$$

In Fig. 2, the input voltage is given from

$$V_{in} = V_{Sp} - V_{Sn} \quad (3)$$

$$V_{Sp} = \frac{1}{3}(V_{San} + aV_{Sbn} + a^2V_{Scn})$$

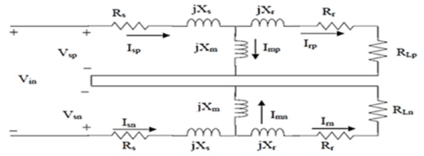

Fig.2 . Sequence Network Connection

$$V_{Sn} = \frac{1}{3}(V_{San} + a^2V_{Sbn} + aV_{Scn})$$

Hence, Eq. (3) can be rewritten as in Eq. (4)

$$V_{in} = \frac{1}{3}(V_{San} - V_{San} + (a-a^2)V_{Sbn} + (a^2 - a)V_{Scn}) \quad (4)$$

In phase form, Eq. (4) will be

$$V_{in} = \frac{V_{Sbc}}{\sqrt{3}} \quad (5)$$

2.1 Equivalent Circuit Analysis

Circuit analysis is best accomplished by first computing the impedances of positive and negative sequences at the system terminal, assuming a slip factor. Suppose the positive sequence slip is S_P. On the other hand, the negative sequence slip is specified as:

$$S_n = 2 - S_p \quad (6)$$

The loaded resistances of the circuits are:

$$R_{ip} = \frac{1-S_p}{S_p}R_r$$

$$R_{in} = \frac{1-S_n}{S_n}R_r = \frac{-1+S_p}{2-S_p}R_r \quad (7)$$

where R_{ip} and R_{in} are the loaded resistance of positive and negative sequences, respectively.

Because the positive sequence slip is generally one or less, the resistance of the negative sequence load should be negative in Eq. (7).

The sequence rotor currents are given by

$$I_{ri} = I_{si} * \frac{jX_m}{jX_m + Z_r + R_{Li}} \quad (8)$$

The sequences of line to neutral stator voltage are:

$$V_{So} = 0 \quad (9)$$

$$V_{Si} = Z_{eqi}I_{si} \quad (10)$$

The equivalent line to neutral stator terminal voltage is:

$$\begin{bmatrix} V_{San} \\ V_{Sbn} \\ V_{Scn} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}\begin{bmatrix} V_{So} \\ V_{Sp} \\ V_{Sn} \end{bmatrix} \quad (11)$$

The line-to-line stator voltage is:

$$\begin{bmatrix} V_{Sab} \\ V_{Sbc} \\ V_{Sca} \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}\begin{bmatrix} V_{San} \\ V_{Sbn} \\ V_{Scn} \end{bmatrix} \quad (12)$$

3. SIMULATION RESULTS

The proposed system block diagram is shown in Fig. 3, which consists of subsystems of inputs of three-phase supply and subsystems of outputs of speed, torque, rotor, and stator currents.

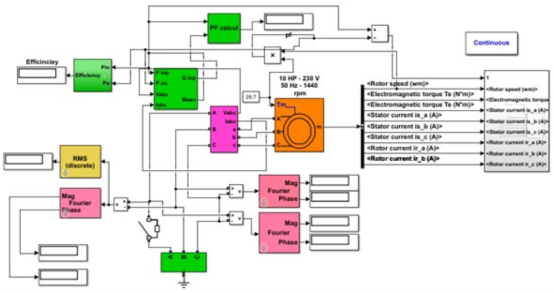

Fig.3. Block diagram of the proposed

3.1 Simulation of balanced and Single Phasing condition

This section considers regular functioning conditions required to create a reference for comparison purposes. This model was run through simulation. In balanced and single phasing modes, the motor was powered by its rated line-to-line voltage of 400 Volt. Single phasing is not typical, but it may be identified following the loss of one phase of a three-phase system, representing the extreme of an unsymmetrical instance, which denotes using a single-phase supply instead of a 3PIM powered by a single-phase supply. This is called "single phasing" because a 3PIM should strive to supply enough of its maximum horsepower to drive the loads if it is operational in a single-phase situation. The simulation technique connected a breaker to one of the three-phase lines to achieve open phasing through motor running. Figures 4 and 5 depict the waveforms of four variables: speed, electromagnetic torque, stator currents, and rotor currents. The used parameters and rated specifications for the motor are listed in Table 1.The results of the stator currents motor at balance and single phasing voltage conditions are listed in Table 2, and the IM parameters result at balance and single phasing voltage conditions are listed in Table 3.

Table 1. Parameters and Rated Specification for the IM

Specifications	Values	Parameters	Values
Rated Power	5.4Hp (4 kw)	Stator resistance R_s	1.405 ohm
Rated Voltage	400/230 V	Rotor resistance R_r	1.395 ohm
Poles	4	Stator inductance L_{is}	0.005839 H
Rotor Speed	1435 rpm	Rotor inductance L_{ir}	0.005839 H
Frequency	50 Hz	Magnetizing L_m	38.9872 H
Connection	Y	Friction factor	0.002985 kg.m2
Phase	3	Moment of Inertia	0.0131

Table 2. Stator currents motor at balance and single phasing voltage conditions

Conditions	I_{as}(peak)	I_{bs}(peak)	I_{cs}(peak)
Balance	$11.06\angle-33.34°$	$11.06\angle-153.33°$	$11.06\angle 86.7°$
Single phasing	$0.0001\angle 25.77°$	$22.74\angle-123.5°$	$22.74\angle 56.5°$

Table 3. Parameters of IM at balance and single phasing voltage conditions

Conditions	speed	$T_{av.}$(N.m)	P_{in}(W)	P_{out}(W)	Losses	p.f.	Effi. %
Balance	1435	27.15	4518	4011	507	0.837	88.78
Single phasing	1376	27.15	5340	3847	1493	0.956	72.04

3.2. Effects of Single Phasing on 3PIM

Almost all stator winding damages in a 3PIM are caused by overheating due to separating one of the source's phases. Because the load on the shaft does not change in these situations, the current in the stator winding rises, and the high heat caused by such current degrades the insulation. The stator current, the magnitude of the source voltage, and the phase angle have been correlated because a stator needs more current to maintain input power stability at low voltage levels, which vary with different sections of an IM and affect the stator winding temperature rise differently. Even if the motor cannot function in a single-phase condition, the torque created by the remaining two positively spinning fields continues to run the motor and provide the torque given by the load. The high

heat generated by the motor windings is mostly due to the passage of negative sequence currents. Parameters of the motor with rated values in Table 4 simplify the comparison of the impacts of a single phasing situation.

Table 4. The motor parameter results under single phasing situations with rating values.

conditions	Stator Current Magnitude	Rotor Current Ripples	Average Speed	Steady State Torque (N.m.) (Settling time)
Balance	Rated	No Ripple	Rated	(0.1 s)
single phasing	Over Rated (double)	No Ripple	Under rated	(0.1 s)

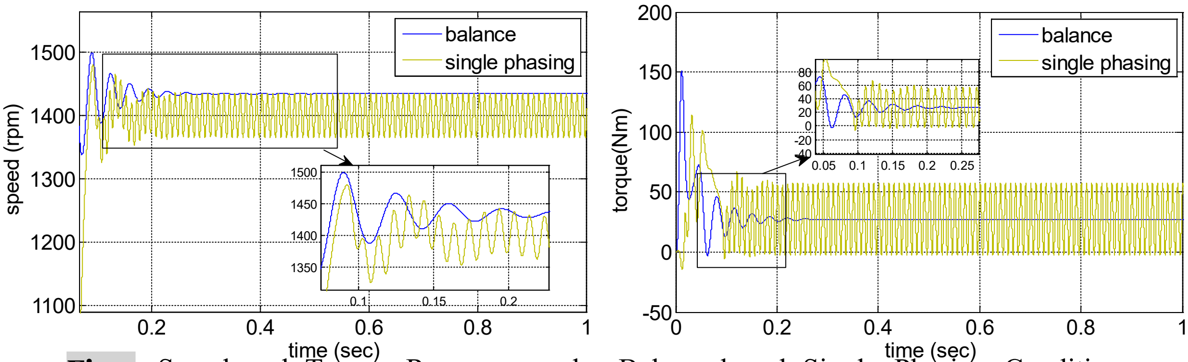

Fig.4. Speed and Torque Response under Balanced and Single Phasing Conditions Algorithm of IM

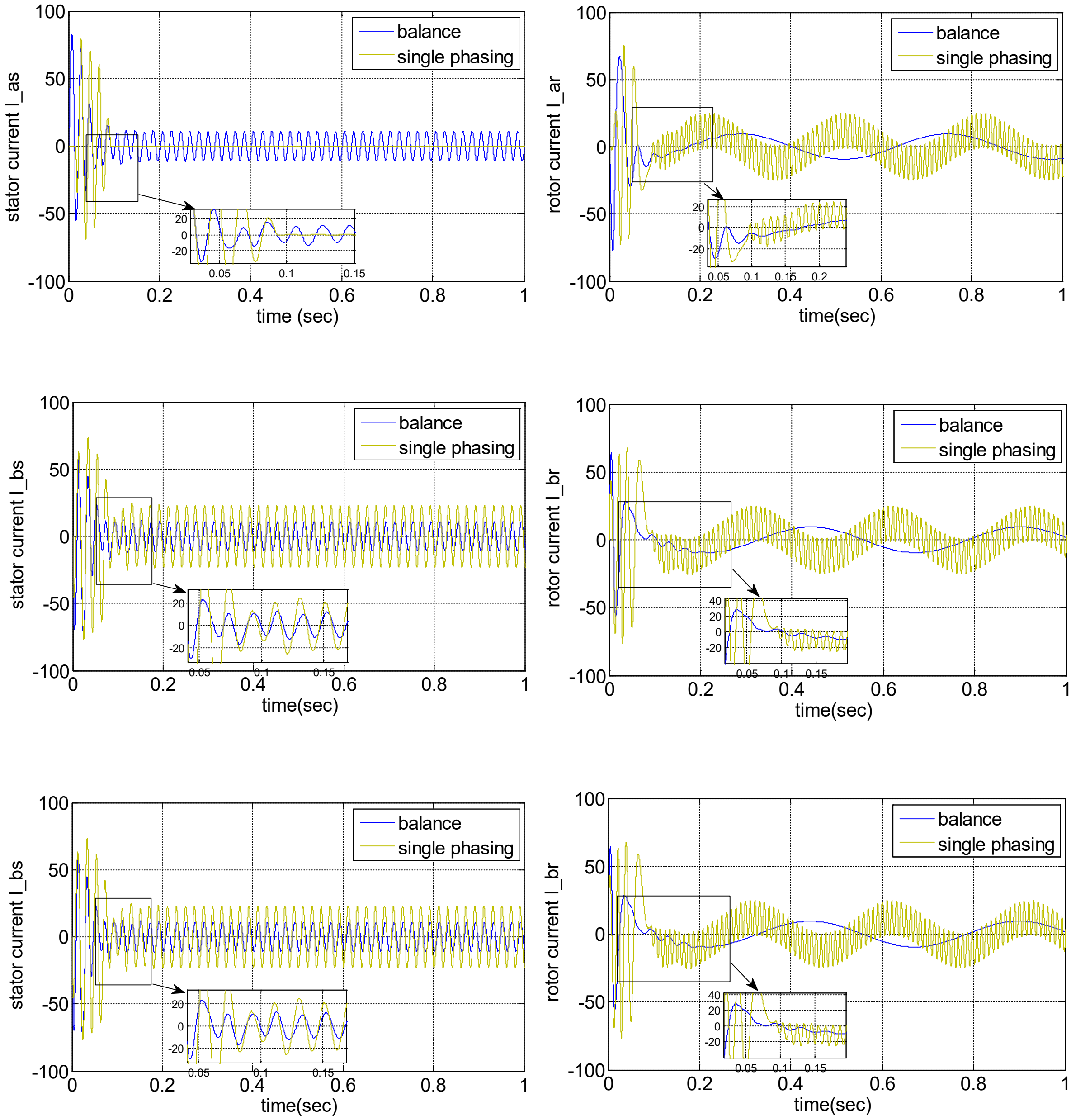

Fig.5. Stator and rotor currents under balanced and single phasing conditions.

It has been noticed that after a transient period of less than 1 sec, the parameters of the IM ,like speed , torque, stator current and rotor current approaches a desired vaule with highly smoothing form.

4. CONCLUSION

Single phasing is an unsafe unbalanced voltage operating situation. Speed decreased marginally; however, currents, heating effects, noise (vibration), and losses increased significantly, resulting in a 16% fall in efficiency, and the power factor rose to 0.965, while currents increased dramatically, causing heating, noise (pulsation), and losses. Therefore, a significant decline in efficiency occurred. Losing one phase significantly increase the stator current to 22.74A compared to 11.06A in the balancing state, as seen in Table 2. There is a relation between the stator current, voltage magnitude, and phase angle because the stator requires more current to keep the input power steady at low voltage levels. In addition, the loss of a phase reduced the rotor speed to 1376 rpm, as seen in Table 2. It caused unstable torque pulsations, unlike any other unbalanced voltage state. Also, the effect was an oscillating torque caused by a highly unstable frequency rotor current. In this situation, it is seen that the efficiency would fall to 72.04%. It should be proposed for further study work to study the functioning and characteristics of big-size 3PIM motors, particularly those utilized for heavy-duty or essential manufacturing processes. It may provide a clearer picture of the unbalanced voltage and voltage harmonic effects.

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