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[Voltage Unbalance Impact on the Characteristics of Three Phase Induction Motor Using Matlab/Simulink]

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الملخص:

تشغيل المحركات الحثية ثلاثية الطور بكفاءة وأداء عالي يمكن تحقيقة عن طريق تغذيتها بمصدر جهد متوازن ثلاثي الطور. يعرف الجهد الغير متوازن المسلط علي المحرك الحثي الثلاثي الطور بأنه الجهد الذي أطواره الثلاثة تختلف في المقدار أو في الزاوية أو كلاهما.في هذة الورقة يتم دراسة تأثير الجهد الغير متوازن سواء بسبب الأختلاف في المقدار أو الزاوية أو كلاهما علي خصائص المحرك الحثي الثلاثي الطور مثل سرعة المحرك والعزم و التيار ومعامل القدرة والكفاءة وغيرها. في هذة الورقة تم ايضا تحليل و دراسة الدائرة المكافئة للمحرك بناءا علي طرق التتابع الموجب والسالب. نتائج هذة الدراسة توضح أن الأختلاف في المقدار والزاوية للجهد المسلط علي المحرك له التأثير الأكثر سلبا علي أداء المحرك مقارنة بالأختلاف في المقدار فقط أو الزاوية فقط.

الكلمات المفتاحية: المحرك الحثي، الجهد الغير متوازن، مقدار الجهد، زاوية الطور.

Abstract:

Three phase induction motors (IMs) are designed to operate under balanced three phase voltage to provide high performance and efficiency. Voltage unbalance at the terminal of three phase IMs exists when the three phase or line voltages differ in magnitude and/or phase shift. In this paper, we study and compare the impact of voltage magnitude unbalance (VMU), voltage phase angle unbalance (VAU), and voltage magnitude and phase angle unbalance (VMAU) on the characteristics of three phase IMs, such as efficiency, power factor, power losses, torque and speed using Matlab/Simulink. In this paper, the equivalent circuit and mathematical analysis of three phase IM based on symmetrical components approach are explained. Simulation results show that the worst effect on the performance of three phase IMs is caused by VMAU, followed by VAU and VMU.

Keywords: Induction Motor, Voltage Unbalance, Voltage Magnitude, Phase Angle.

1. Introduction

Induction motors (IMs) are broadly utilized for industrial, commercial and residential applications. IMs are expected to represent 90% of electric motors and consume more than half of the world electric energy [1] [2]. In industries, around 70 % of the electric energy consumption goes to electric motors and it is found that 85-90% of this consumption goes to three phase IMs only [3], [4]. This large amount of consumed energy is due to the low power factor resulting from the reactive power drawn by IMs being inductive loads [5]. The extensive use of IMs is due to their significant advantages over other types of electric motors like DC motors. These features include simple and robust structure, low maintenance, cheaper in cost, and high efficiency at full load operation. To avoid reduction in the operating lifetime and performance of IMs and save electrical energy consumption, IMs should be driven within the allowable limits of voltage, current and frequency variations. Unbalanced voltage is a voltage quality issue and considered as one of the power quality disturbances [6]. There are various factors through which the voltage (at the utilization end) becomes unbalanced. Some of these are: open delta transformer connections, unbalance of single-phase loads, blown fuses on three phase capacitors banks, unsymmetrical impedances of transformer windings, and faults in power system [7], [8],[9]. Unbalanced voltage can be categorized into overvoltage unbalance (OVU) where one phase or two phases are above the rated voltage or all three phases are greater than the rated voltage, undervoltage unbalance (UVU) where one phase or two phases are below the rated voltage or all three phases are less than the rated voltage, and unbalanced phase angles where all three phase voltages are equal in magnitude, but one or two of the phase angles are different [9]. In actual practice, other categories of unbalanced voltage can also exist [9]. When a three phase IM is subjected to unbalanced voltage, unbalanced currents will be present in the stator windings. The resulting unbalanced currents can be expressed in terms of symmetrical components approach. As the stator windings of three phase IMs are connected in delta or 3-wire star (i.e., the neural wire between the voltage source and motor is not present), the zero-sequence current is equal to zero [10]. Thus, unbalanced currents flowing through three phase IMs are expressed only by the positive and negative sequence currents. The positive sequence current establishes a rotating magnetic field that spins at synchronous speed in the same direction as the rotor, whereas the negative sequence current creates a rotating magnetic field that spins at synchronous speed in a direction opposite to that produced by the positive sequence [10]. The positive sequence current sets up a positive electromagnetic torque, which is effectively the same as the one produced by applying a balanced voltage, while the negative sequence current delivers a negative electromagnetic torque. As a result, the net electromagnetic torque generated from unbalanced voltage is the sum of the positive and negative electromagnetic torque. This net electromagnetic torque is always less than the electromagnetic torque produced by a balanced voltage. Voltage unbalance considering the magnitude only is generally defined by two international standards, namely, the National Electrical Manufacturer Association (NEMA) and the International Electrotechnical Commission (IEC) [11]. The former, known as percent voltage unbalance (PVU), defines the voltage unbalance as the ratio of maximum line voltage deviation from the average line voltage to the average line voltage of three voltages, while the latter, known as voltage unbalance factor (VUF), defines the unbalanced voltage as the ratio of the negative sequence voltage to the positive sequence voltage [11] [12]. To study the impact of unbalanced voltage comprehensively, the unbalance in phase angle should be also taken into account. Thus, other voltage unbalance definitions, considering the phase angle and stator current, have been used in many research papers. These include the complex voltage unbalance factor (CVUF) that is determined by the ratio of the voltage phasor of the negative sequence to the voltage phasor of the positive sequence, the stator current unbalance factor (CUF) that is defined by the ratio of the stator current magnitude of the negative sequence current to the stator current magnitude of the positive sequence, and the complex stator current unbalanced factor (CCUF) that is expressed by the ratio of the stator current phasor of the negative sequence to the stator current phasor of the positive sequence [11], [13]. The topic of voltage unbalance is important to investigate, being essentially related to the energy saving and motor performance. The impact of unbalanced voltage on three phase IMs has latterly received a lot of research attention.

The authors of [12], [14], [15], [16] reported that operating three phase IMs under unbalanced voltage results in pulsating speed and torque, speed reduction, vibrations, and noise. The impact of voltage unbalance on three phase IM characteristics, such as motor losses, efficiency, line currents and temperature were discussed in [17], [18]. In [19], a comparison between the effect of voltage magnitude unbalance and phase shift unbalance on three phase IM was introduced. At the same percentage of unbalance, the results showed that the phase shift unbalance has more effect on power factor, efficiency, losses, reactive power, and apparent power than voltage magnitude unbalance. In [20], the impact of open phase fault that occurs during motor operation on a three phase IM was investigated experimentally. In [21], a comparison between the effect of mechanical overload and unbalanced voltage on three phase IM temperature was carried out experimentally. At the same percentage of mechanical overload and voltage unbalance, the results showed that the temperature increase due to voltage unbalance is higher than the temperature rise generated from mechanical overload.

This paper investigates and compares the impact of voltage magnitude unbalance (VMU), voltage phase angle unbalance (VAU) and voltage magnitude and phase angle unbalance (VMAU) on three phase IM performance using MATLAB/SIMULINK.

2. Equivalent circuit of three phase induction motor under voltage unbalance

Three phase IM under voltage unbalance is analyzed by symmetrical components methods. Due to the absence of the neural wire between the supply and motor, the zero-sequence equivalent circuit is not considered. Therefore, the equivalent circuit is represented only by two separate equivalent circuits, one is called positive sequence equivalent circuit and the other is called negative sequence equivalent circuit as shown in Fig. 1 and Fig. 2. The positive and negative sequence equivalent circuits are the same as the equivalent circuit represented under balanced voltage except that the slip in negative sequence circuit is 2 - the slip of the origin system. This is because the magnetic flux produced by negative sequence current is rotating opposite to the motor shaft.

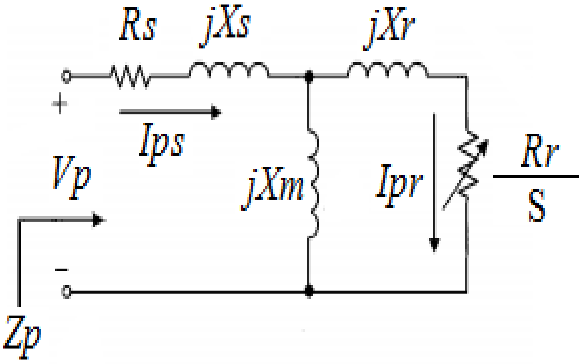

Fig. 1. Positive equivalent circuit.

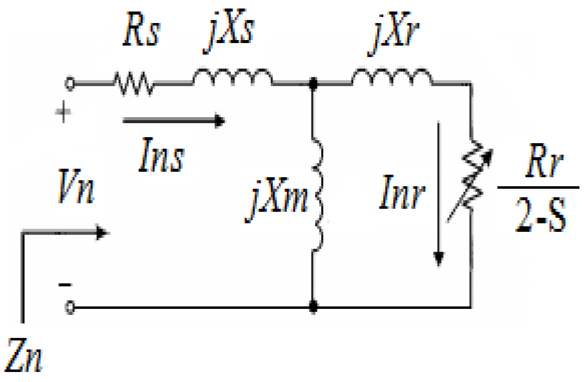

Fig. 2. Negative equivalent circuit.

In Fig.1 and Fig. 2, R_s, jX_s, and jX_m, are stator winding resistance, stator leakage reactance and magnetizing reactance respectively, R_r, and jX_r, are rotor resistance referred to stator and rotor leakage reactance referred to stator respectively, V_p, I_{ps} and I_{pr} are positive sequence voltage of the stator, positive sequence current of the stator and positive sequence current of the rotor referred to stator respectively, V_n, I_{ns} and I_{nr} are negative sequence voltage of the stator, negative sequence current of the stator and negative sequence current of the rotor referred to stator respectively, Z_p and Z_n are total impedance of positive equivalent circuit and total impedance of negative equivalent circuit respectively, and S is the motor slip under balanced condition. By applying symmetrical components approach, the line currents drawn by the motor can be calculated as:

$$V_p = \frac{1}{3}(V_a + aV_b + a^2V_c) \tag{1}$$

$$V_n = \frac{1}{3}(V_a + a^2V_b + aV_c) \tag{2}$$

$$Z_p = R_s + jX_s + jX_m\left(\frac{jX_r+\frac{R_r}{s}}{jX_m+jX_r+\frac{R_r}{s}}\right) \tag{3}$$

$$Z_n = R_s + jX_s + jX_m\left(\frac{jX_r+\frac{R_r}{2-s}}{jX_m+jX_r+\frac{R_r}{2-s}}\right) \tag{4}$$

$$I_{ps} = \frac{V_p}{Z_p} \tag{5}$$

$$I_{pr} = I_{ps}\frac{jX_m}{jX_m+jX_r+\frac{R_r}{s}} \tag{6}$$

$$I_{ns} = \frac{V_n}{Z_n} \tag{7}$$

$$I_{nr} = I_{ns}\frac{jX_m}{jX_m+jX_r+\frac{R_r}{2-s}} \tag{8}$$

$$I_a = I_{ps} + I_{ns} \tag{9}$$

$$I_b = a^2 I_{ps} + aI_{ns} \tag{10}$$

$$I_c = aI_{ps} + a^2 I_{ns} \tag{11}$$

Where V_a, V_b and V_c are the applied phase voltages, I_a is the current of phase a, I_b is the current of phase b, I_c is the current of phase c and a is called the operator and is equal to $1e^{j120^0}$.The motor characteristics such as input power, output power, power losses, motor torque, power factor can be written as:

$$P_i = \mathrm{Re}\{3(V_p I_{ps}^* + V_n I_{ns}^*)\} \tag{12}$$

$$Q_i = \mathrm{Im}\{3(V_p I_{ps}^* + V_n I_{ns}^*)\} \tag{13}$$

$$p.f = \cos[\tan^{-1}(\frac{P_i}{Q_i})] \tag{14}$$

$$P_s = 3I_{pr}^2 R_r \left(\frac{1-s}{s}\right) \tag{15}$$

$$P_s = 3I_{pr}^2 R_r \left(\frac{s-1}{2-s}\right) \tag{16}$$

$$P_o = P_s + P_n \tag{17}$$

$$T_s = \frac{P_s}{w} \tag{18}$$

$$T_n = \frac{P_n}{w} \tag{19}$$

$$T = T_s + T_n \tag{20}$$

$$P_l = P_i - P_o \tag{21}$$

$$\eta = \frac{P_o}{P_i}\ \% \tag{22}$$

Where P_i, Q_i and p.f are the input power, reactive power and power factor respectively, P_s, P_n and P_O are output power of positive sequence, output power of negative sequence and net output power respectively, T_s, T_n and T are the positive sequence torque, negative sequence torque and net torque respectively, P_s is the total losses and η is the motor efficiency.

3. Methodology

The motor simulated in this work is three phase squirrel cage induction motor, Y-Y connection, 10 HP, 460 V, 60 Hz, 1760 rpm and has the following parameters:

$R_S = 0.68\ \Omega,\ X_S = 1.56\ \Omega,\ R_r = 0.45\ \Omega, X_r = 1.56\ \Omega$ and $X_m = 56\Omega$

Under balanced condition, the motor is fed by its rated phase voltage that is $\frac{460}{\sqrt{3}}$ V. Under VMU, phase b magnitude is increased by 15% and phase c magnitude is decreased by 15%. Under VAU, a 15% increase is in phase b angle and a 15% decrease is in phase c angle. Under VMAU, magnitude and angle of phase b are increased by 15%, while magnitude and angle of phase c are decreased by 15% as shown in table (1).

Table (1): Balanced and unbalanced voltage conditions

Condition	Phase a	Phase b	Phase c
Balanced voltage	265.58∟0	265.58∟-120	265.58∟120
VMU	265.58∟0	305.41∟-120	225.74∟-120
VAU	265.58∟0	265.58∟-138	265.58∟102
VMAU	265.58∟0	305.41∟-138	225.74∟-102

4. Simulation results and discussion

Simulink model is built to investigate the operation of three phase IM under balanced and unbalanced conditions. The motor characteristics obtained from the simulation results are displayed in time domain.

Fig. 3 and Fig. 4 show the electromagnetic torque and rotor speed waveforms under balanced voltage, VMU, VAU and VMAU. As we can see when the motor reaches steady state in about 0.8 seconds, the electromagnetic torque and rotor speed waveforms contain ripples (pulsating) when operating under VMU, VAU and VMAU. We can notice that the increase in speed with time under VMAU is lower and it takes long time for the motor to reach steady state. We can also observe that the ripples resulting from VMAU are higher compared with VMU and VAU. These ripples cause vibration, which in turn reduces the lifetime of motor mechanical parts.

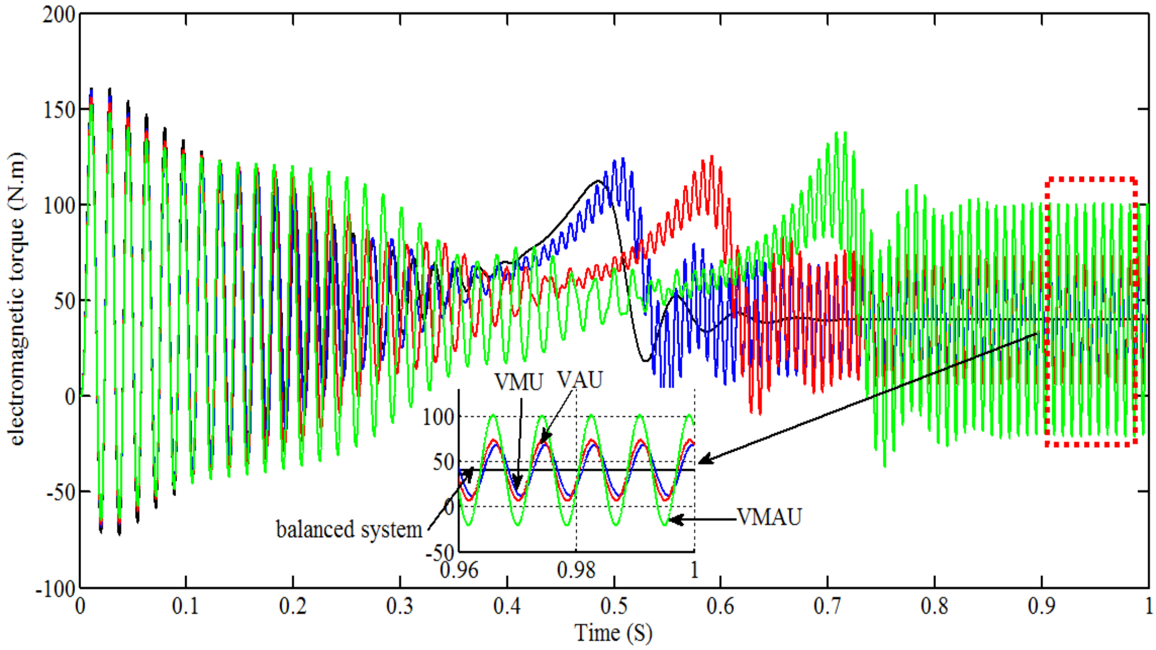

Fig.3. Electromagnetic torque under balanced voltage, VMU, VAU and VMAU.

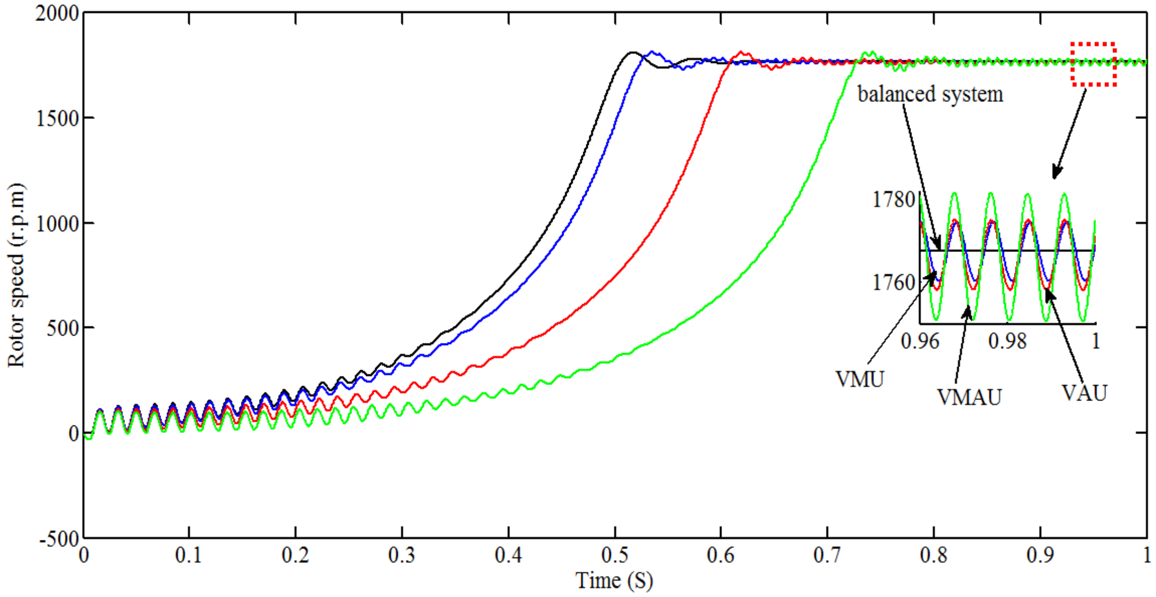

Fig.4. Rotor speed under balanced voltage, VMU, VAU and VMAU.

Fig. 5, Fig. 6 and Fig. 7 show the phase currents (or line currents as the connection is (Y-Y) waveforms under balanced voltage, VMA, VAU and VMAU. It is clear from the currents' waveforms that the currents are unbalanced when operating under VMA, VAU and VMAU and the higher currents are produced by VMAU. It is also shown that the time for the motor to reach steady state is less when operating under balanced voltage.

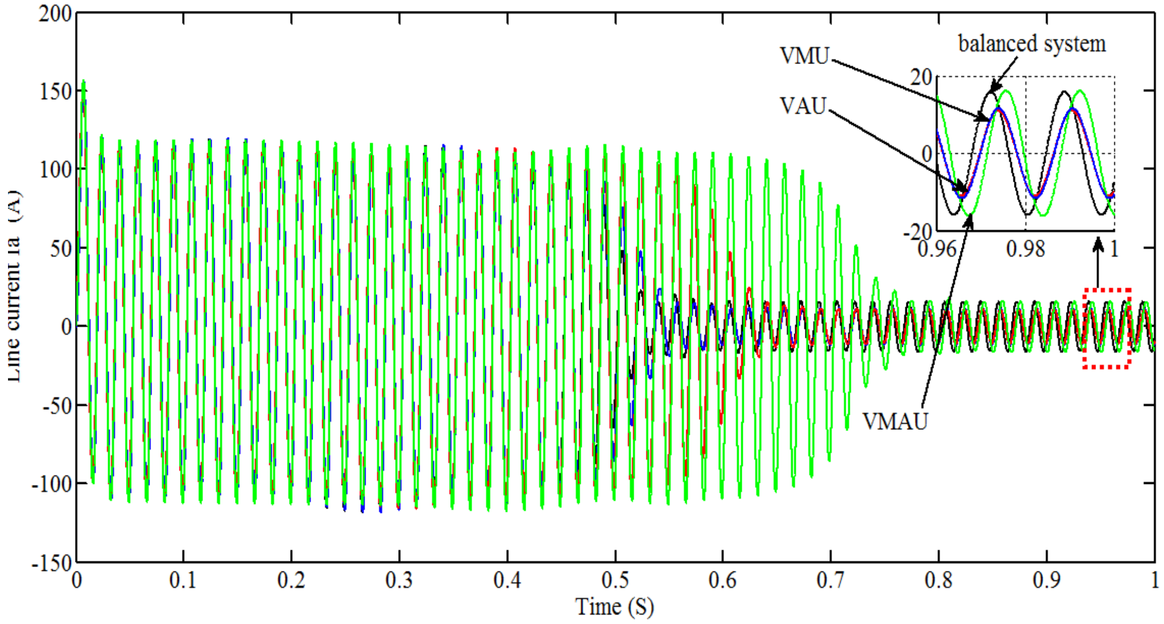

Fig.5. Line current Ia under balanced voltage, VMU, VAU and VMAU.

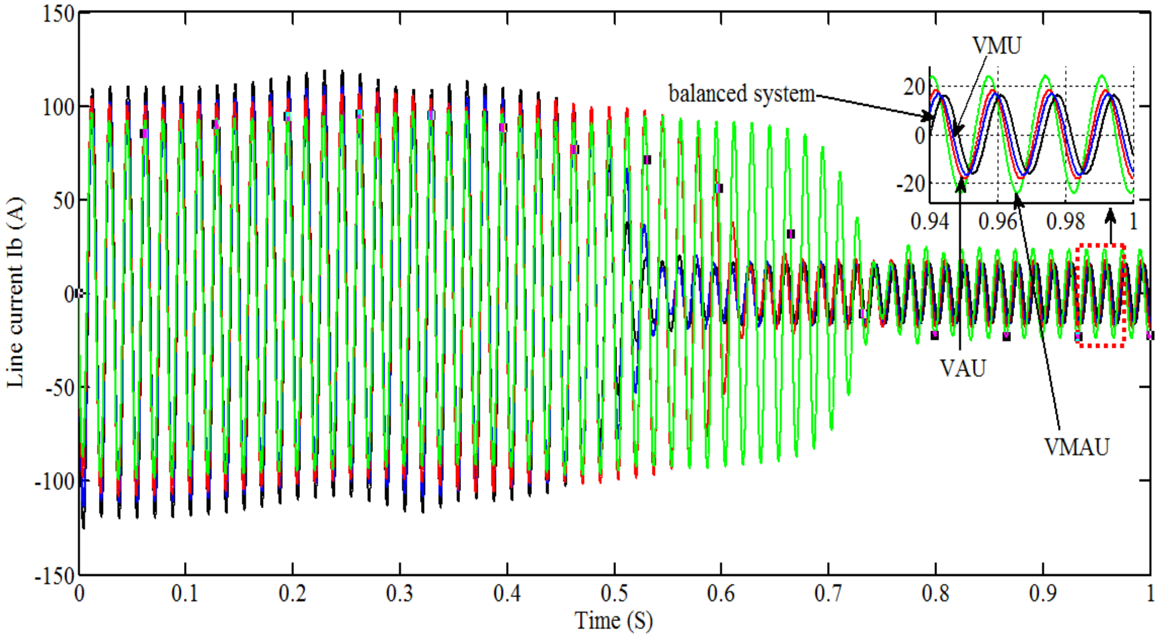

Fig.6. Line current Ib under balanced voltage, VMU, VAU and VMAU.

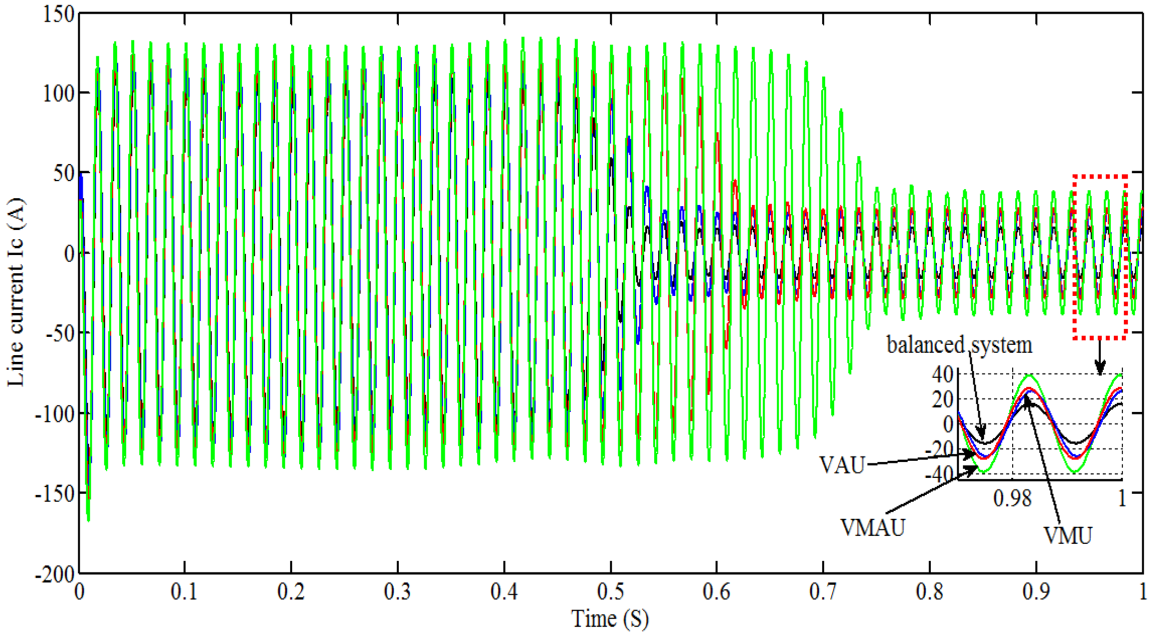

Fig.7. Line current Ic under balanced voltage, VMU, VAU and VMAU.

Fig. 8, Fig. 9 and Fig. 10 show the waveforms of total input power, total apparent power and total power losses under balanced voltage, VMA, VAU and VMAU. As the higher currents are produced by VMAU, the total input power, total apparent power and total power losses are also higher compared to balanced voltage, VMA and VAU.

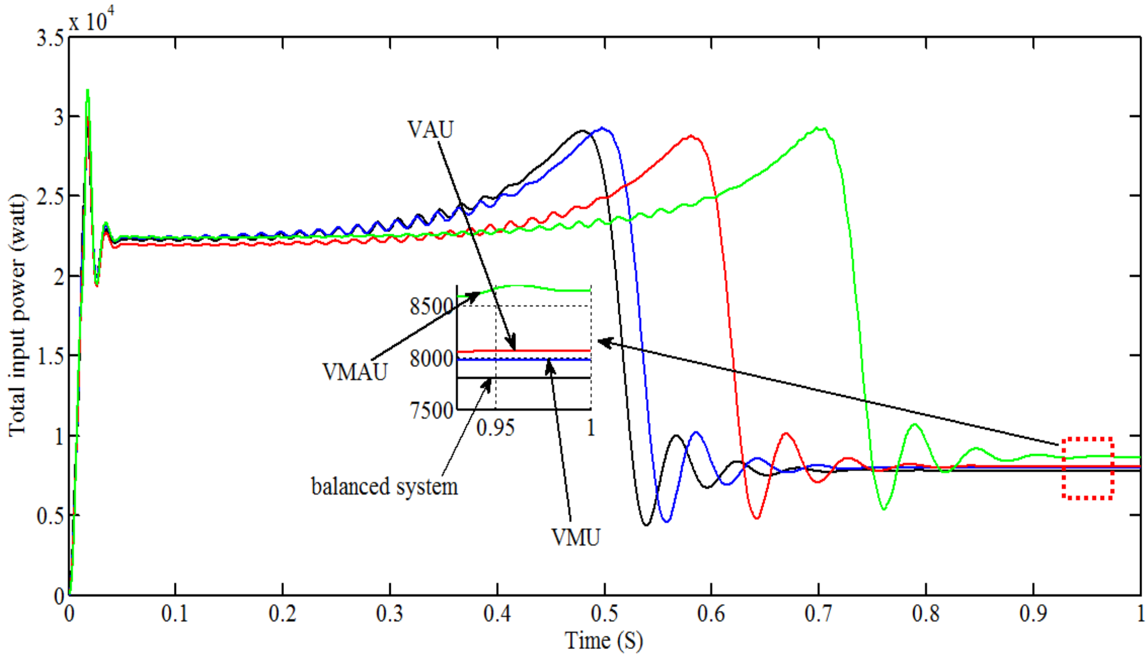

Fig.8. Total input power under balanced voltage, VMU, VAU and VMAU.

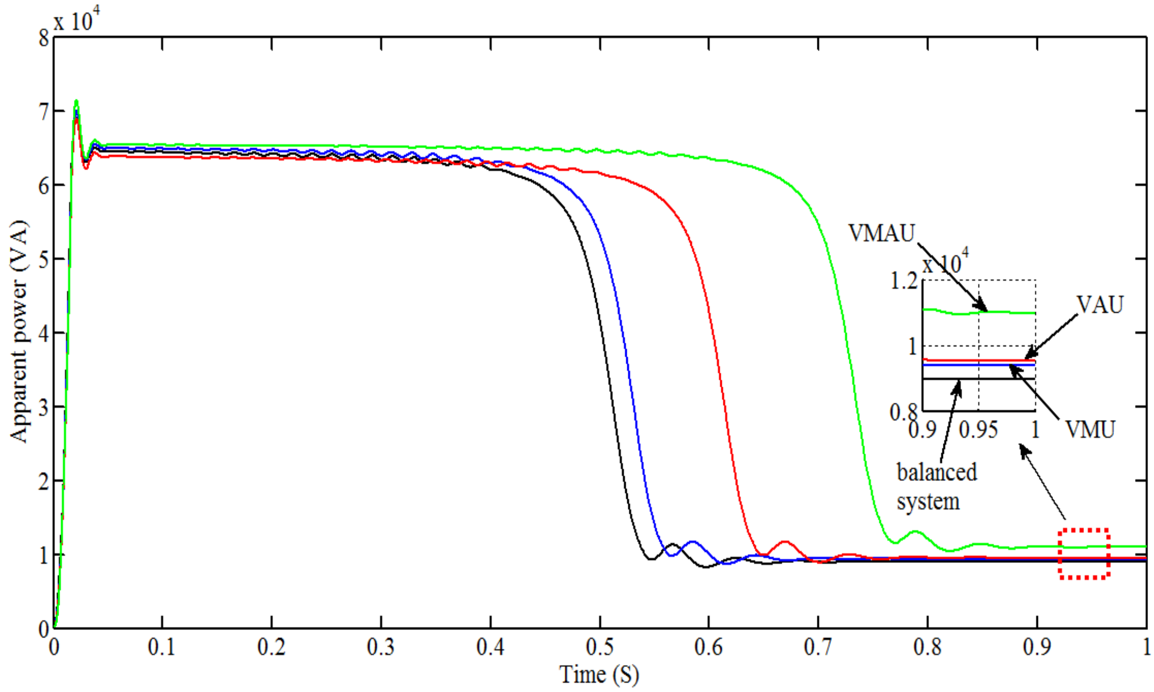

Fig.9. Total apparent power under balanced voltage, VMU, VAU and VMAU.

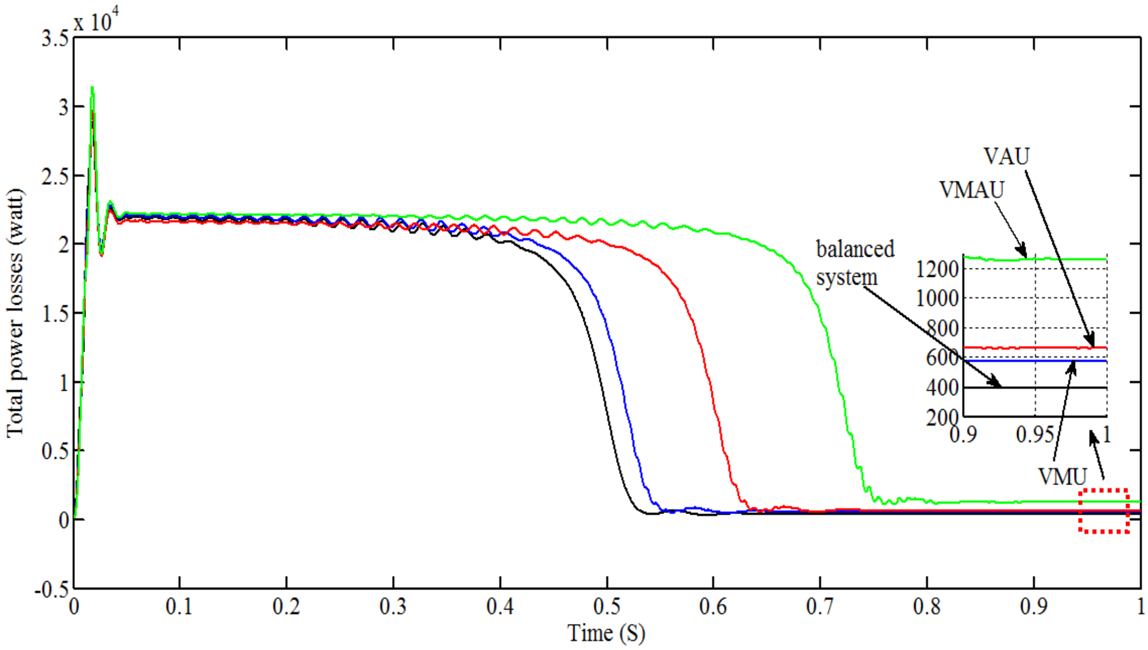

Fig.10. Total power losses under balanced voltage, VMU, VAU and VMAU.

Fig. 11 and Fig. 12 and Fig. 13 illustrate the motor efficiency, power factor and output power waveforms under balanced voltage, VMU, VAU and VMAU. As shown from these figures, the motor efficiency, power factor and output power under VMAU are lower compared with balanced voltage, VMU and VAU.

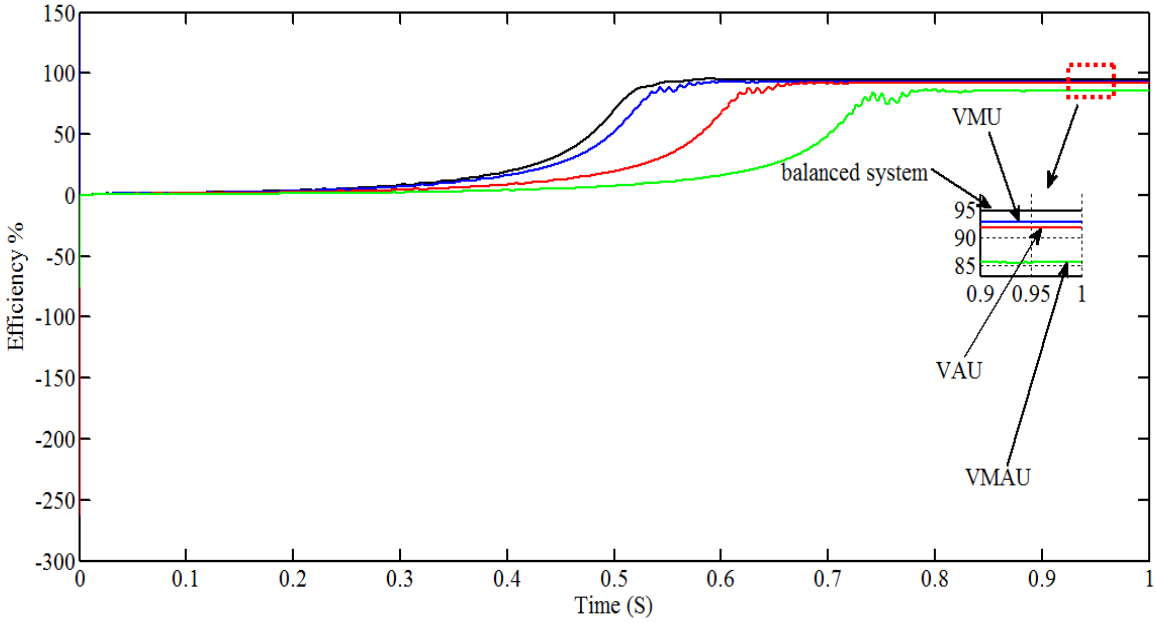

Fig.11. Efficiency under balanced voltage, VMU, VAU and VMAU.

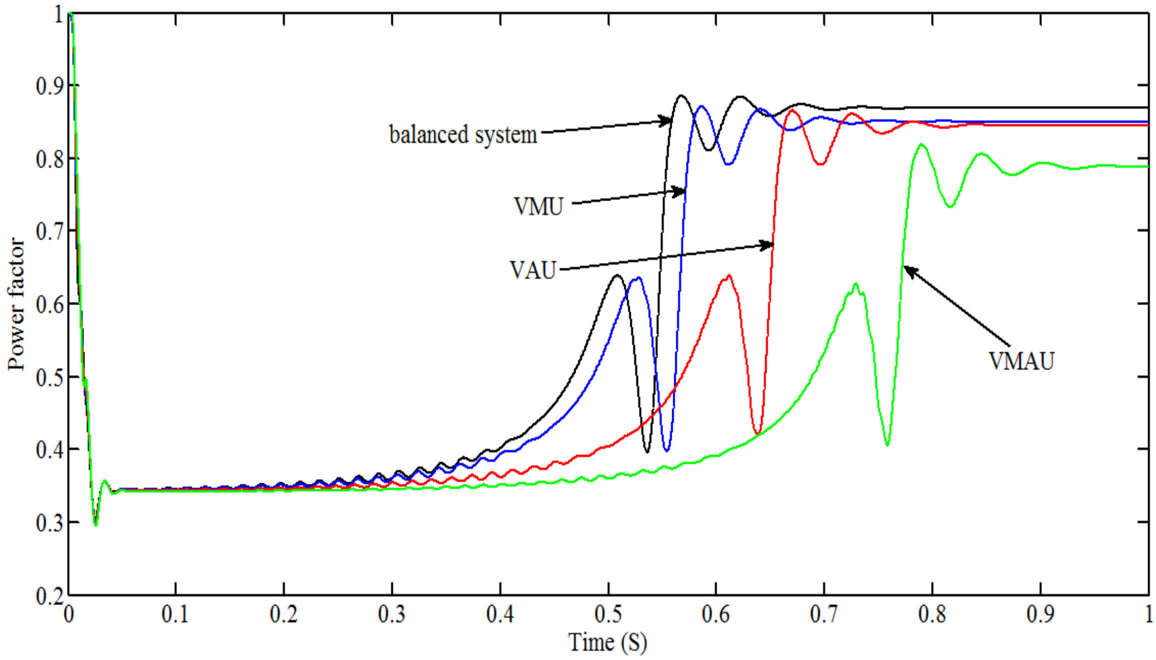

Fig.12. Power factor under balanced voltage, VMU, VAU and VMAU.

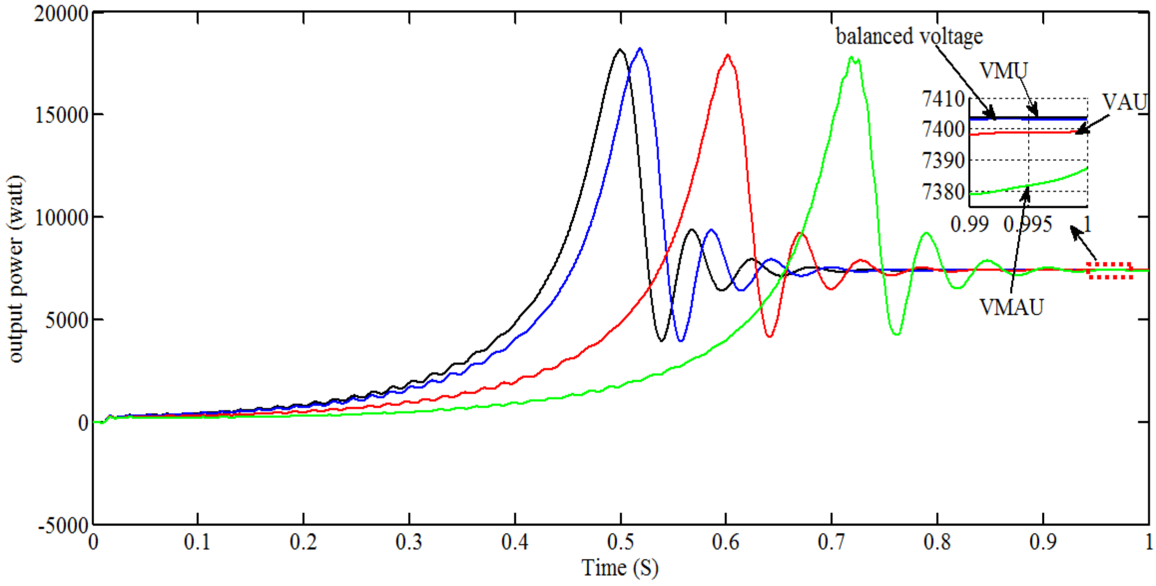

Fig.13. Output power under balanced voltage, VMU, VAU and VMAU.

5. Conclusion

In this work, we studied the effect of VMU, VAU, and VMAU on the characteristics of three phase squirrel cage IM using MATLAB/SIMULINK. A comparison between the three scenarios has been carried out to find which one has the worst impact on the motor performance. Simulation results demonstrated that the torque and speed ripples, line currents, power losses, input power and apparent power are higher when operating under VMAU compared with VMU and VAU. Also, under VMAU, efficiency and power factor are lower compared with VMU and VAU. Operating three phase IMs under any condition of voltage unbalance mentioned in this paper causes problems such as overheating, vibrations, noise, insulation damage, and an increase in line power losses and voltage drop due to the increase in line currents. Therefore, it is important to ensure that the three phase IMs are driven within the voltage unbalance limit specified by NEMA and IEC to avoid reducing in motor lifetime and increasing in electric bill.

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