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On The Natural Frequency of Oscillations of Induction Motors

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Abstract

For transient stability analysis, the rotor dynamics of the induction motor have to be included. These dynamics affect the system stability when severe disturbances hit it and cause frequency deviations. For large systems, frequency deviations are small. However, it may cause loss of synchronism and break the system into smaller areas. Motor loads are sensitive to system frequency deviations. Any change in the grid frequency, changes extremely the slip. This follows by changes of the motor torque and the motor speed. The demanded active and reactive powers change as well. Natural frequencies of induction motors is considered a unique property has a great effect on its behavior during different operation conditions. This work presents the performance of the induction motors through different power systems. Based on time domain simulation models study the natural frequency of induction motors, their response in normal and abnormal operation is analyzed to illustrate the dynamics associated.

Keywords

Natural frequency; Induction motor loads; and Power system stability

1. Introduction

More than 60% of the consumption of the generated electrical power is engorged by the asynchronous motors [1]. In transient stability analysis, the dynamic of the stator are completely ignored [2]. This is the main reason that during the following analysis the rotor speed of all types of machines is considered the dominate feature to study the power system performance. Besides, instead of using hard long method, during this work simulated models of different systems are presented in time domain simulation. These simulated models represent fast transients during impacts and after reaching stability again. This work illustrates the behavior of induction motor in the natural frequency point of view, electrically and mechanically. This paper consists of 10 sections including the introductory section to discuss the concept of the natural frequency for an induction motor.

2. Induction motor in power grid:

Figure (1) shows an induction motor supplied by the power grid.

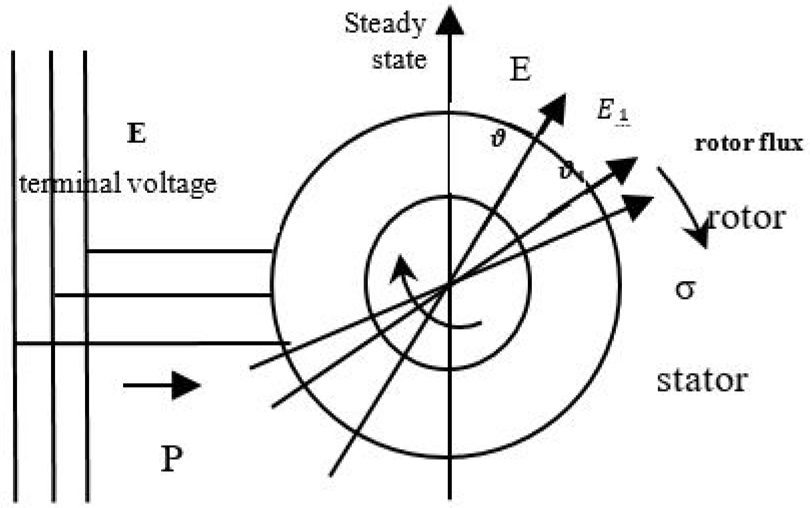

Figure 1. Induction motor connected to grid.

This figure shows an induction motor connected to a power network with terminal voltage E with a deviation $\vartheta$from a stationery vector called steady state voltage vector. When the induction motor rotor glides against the rotating flux, an electrical power is going to be developed. This produced power is taken from the power system and is given by, [3]:

$$P = P_0 \frac{\sigma}{\sigma_a} \tag{1}$$

Where, P_0 is the motor rated electrical power, σ is the rapid slip given by the change of the rotor electrical angle and its flux and σ_a is the asynchronous normal slip which is usually assumed to be 0.5 to 5 to 10 per cent.

Due to the motor leakage flux, the effective flux of the rotor has a phase displacement against the terminal voltage of the stator. This leakage flux is associated with leakage angleϑ_1 and instantaneous leakage voltageE_1 . This deviation between the rotor flux and the terminal voltage is represented by:

$$\vartheta_1 = \frac{E_1}{E} = v_1 \ \frac{P}{P_0} \tag{2}$$

Where, v_1 is the leakage voltage and for most of the induction motors is assumed to be 20 to 30 per cent. The energy law illustrates the relationship of the deviation of the electrical power due to the exchanged power between the motor and the grid to be:

$$P + \sigma_a T_a \frac{dp}{dt} + \frac{v_1 t_a}{\omega} \frac{d^2 p}{dt^2} = -\frac{T_a P_0}{\omega} \frac{d^2 \vartheta}{dt^2} \tag{3}$$

This shows that if the angle of the network ϑ changes, the induction motor oscillates. Even in the case of a steady state grid, it may suffers transient oscillations according to its natural frequency given when the right hand side of (3) equals zero. The resulted power transferred between the grid and the rotor due to these oscillations is given by:

$$P" = \overline{P} e^{-\frac{P}{2}t} \cos \mu t \tag{4}$$

Where, $\overline{P}$ is the free oscillations amplitude, $\rho$is the damping factor and μ is the motor natural frequency.

3. Natural frequency of an induction motor:

If there is an induction motor with rated slip $\sigma_a$equals 1 per cent, an accelerating time constant Ta equals 2.5 second and leakage voltage v_1 equals 29 per cent. This induction motor is connected to an infinite network as shown in Figure (1). The damping factor is given by:

$$\frac{\rho}{2} = \frac{\omega\sigma_\alpha}{2v_1}$$
$$then,\ \frac{\rho}{2} = \frac{377\times 0.01}{2\times 0.29} = 6.5 \tag{5}$$

The natural frequency of an induction motor is given by:

$$\mu = \sqrt{\frac{\omega}{v_1 T_a} - \left(\frac{\rho}{2}\right)^2}$$
$$then,\ \mu = \sqrt{\frac{377}{0.29\times 2.5} - (6.5)^2} = 3.3\ cps. \tag{6}$$

By using SIMULINK tool in the MATLAB software to simulate such a system, the resulted oscillations of this motor while plugging it with the network is given in Figure (2), where the rotor speed is plotted against time, as:

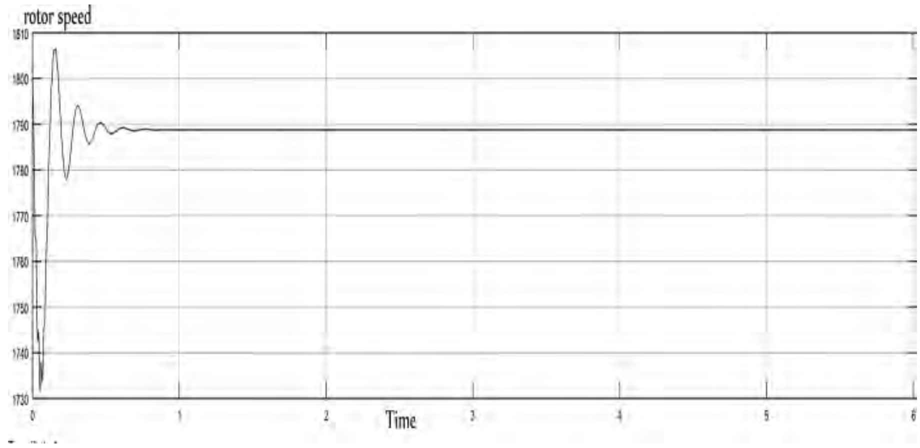

Figure 2. Oscillations of IM connected to grid.

By comparing the results from the formula of [3] and the one shown in Figure (2), they are almost identical.

For each speed change of an induction motor, it produces free oscillations. These oscillations are sliding aperiodically in the case of large rated slip. In the start, the induction motor may overshoot the synchronous speed. Free transient oscillations are resulted and then they have to be completely damped to guarantee stable operation. The exchanged power between the grid and the motor increases greatly if the motor operates within the range of its resonance zone [3].

The induction motor performs oscillations with its natural frequency when connected to the grid. This frequency is going to be different if connected together with other machines.

4. Oscillations between synchronous generators and induction motors:

For transient behavior analysis of a synchronous generator, each single generator behavior has to be studied individually. In contrast, the analysis of induction motors is considered all of them jointly.

Figure (3) illustrates an equivalent diagram to this analysis, where there are number ”g” of synchronous generators feed a bus bar. All the induction motors ”n” are supplied from this bus bar and drawn jointly together with total kinetic energyΣG_n . For interconnected power systems, the rotating masses of all the connected induction motors are affect the oscillations of the feeding synchronous generators. For an interconnected system, that consists of two synchronous generators connected in parallel to feed two induction motors as shown in Figure (4), each machine oscillates depending on its natural frequency.

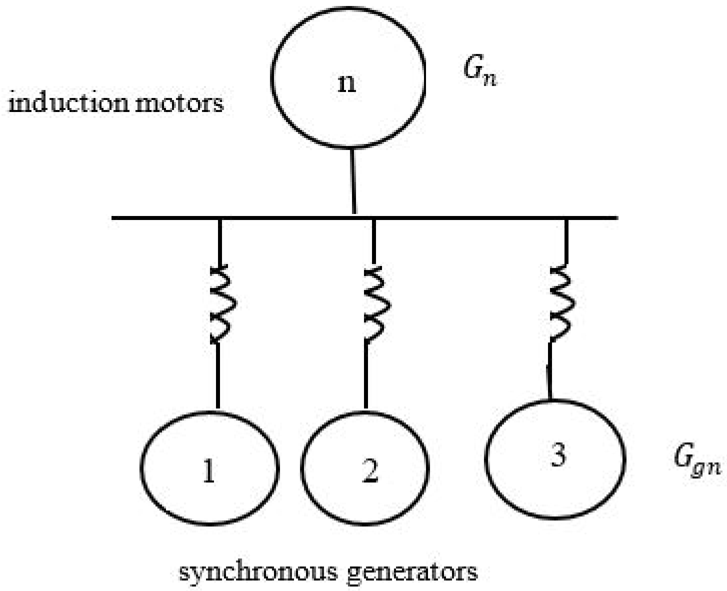

Figure 3. Power system equivalent diagram

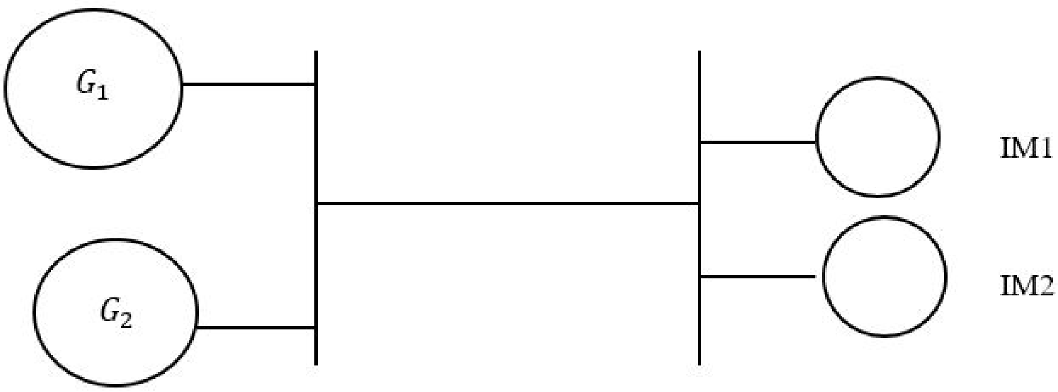

Figure 4. Two SG connected to two IM

After the oscillations are damped, the natural frequencies of these machines never intersect together. They remain parallel [3]. According to [3], when a power system is disturbed by any perturbation, the masses of all the interconnected machines oscillate trying to reach a balanced state of operation. The power balance described this behavior is expressed as:

$$G_1 \frac{v_1^2}{v_1^2 - v^2} + G_2 \frac{v_2^2}{v_2^2 - v^2} + G_3 \frac{v_3^2}{v_3^2 - v^2} + \cdots = -\sum G_n \quad (7)$$

Where, G_1, G_2, G_3, ... are the kinetic energy of the synchronous generators and v_1, v_2, v_3 are the natural frequency of each synchronous generator. v is the natural frequency of the whole system.

(7) is presented graphically in Figure (5).

In this figure, $\Sigma G_n$is the total kinetic energy of the connected induction machines and $\Sigma G_g$is the total kinetic energy of the connected synchronous machines.

This system shown in Figure (4) is simulated using SIMULATION tool in MATLAB. The simulated model represents the start of applying the two induction motors to be fed by the two synchronous generators and lasts for 10 seconds. The system performance is analyzed by studying the speeds of all machines rotors, as shown in Figure

(6).

The upper two lines represent the rotors speeds of the two synchronous generators. Each one oscillates according to its natural frequency. Then settle together with the same natural frequency. While the lower two lines represent the rotors speeds of two induction motors. As shown the lines are never intersect.

This simulated system shows that not only the induction motors natural frequencies are not intersect with these of the synchronous generators, but the natural frequencies of the induction generators are not intersect with them as well. If a huge power impact hits this system, the induction motor with a large time constant may suffer an overloading condition compared to its rated power [3].

According to [3], all the interconnected parallel synchronous generators oscillate in perfect harmony. They oscillate together against all the supplied induction motors, which is proved by the previous simulated model. This system has the maximum possible stable performance. It is hard to lose synchronism among its generators.

Due to the slip effect, which is slow comparing to the synchronous generators [1], the initial distribution of an impact among synchronous generators and induction motors is different. Synchronous generators respond instan-

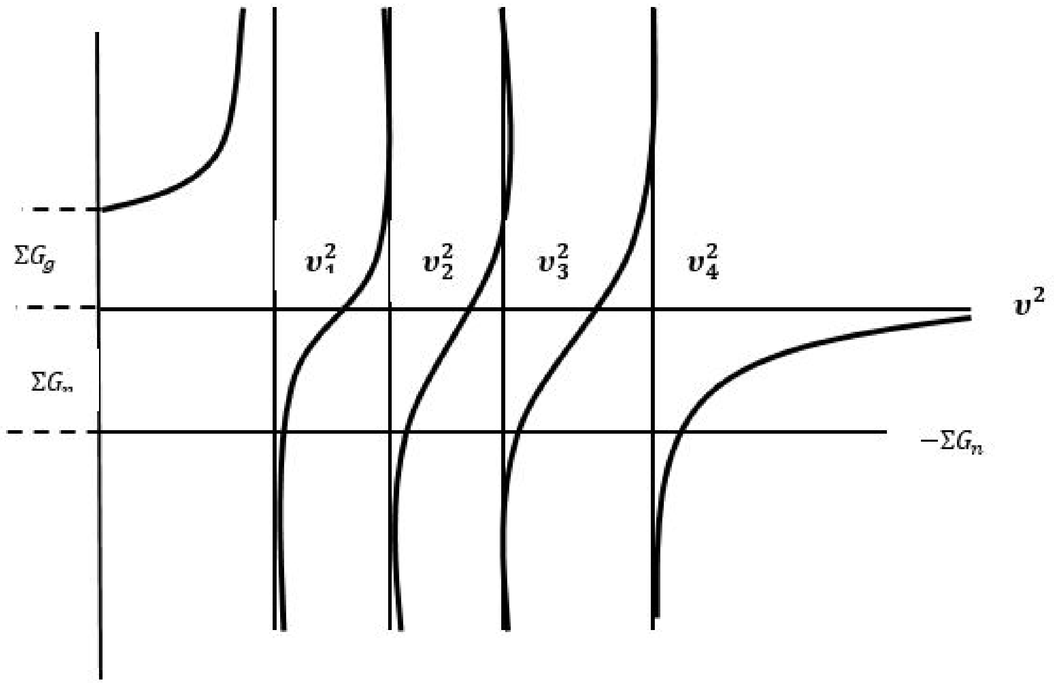

Figure 5. Graphical representation of all machines natural frequencies

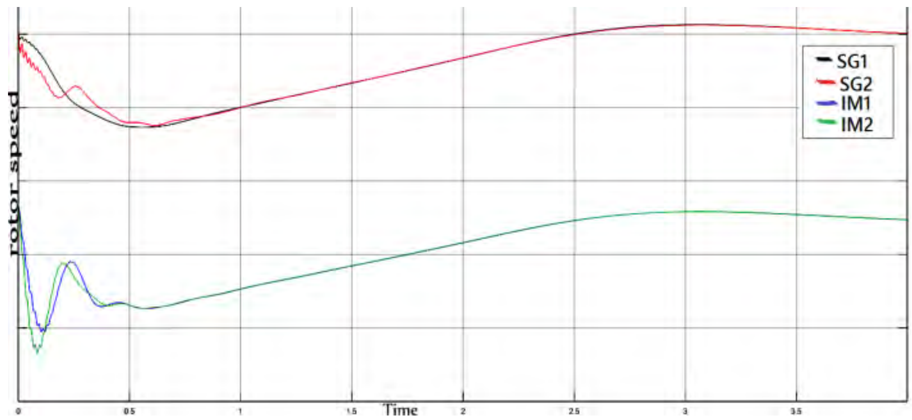

Figure 6. Oscillations of the system

taneously as shown in Figure (7), [3]:

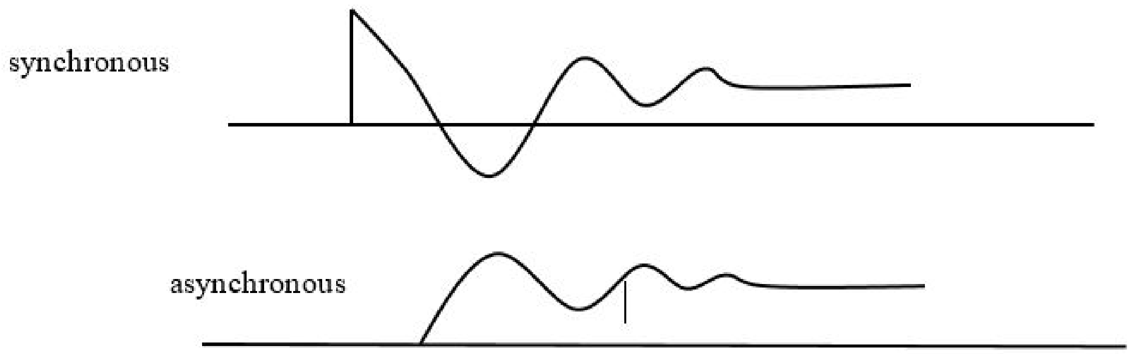

Figure 7. Different response of SG and IM

5. Case study:

If there is a power system consists of two synchronous generators with 4.125 MVA and 3.125 MVA as their rated powers. As for their inertia constants, they are 4.07 second and 1.07 second, respectively. They are supplying three induction motors with different parameters such as their inertia coefficients and leakage voltages. A doubly fed induction generator in a wind farm is also connected to this system. Figure (8) represents a single line diagram for this system.

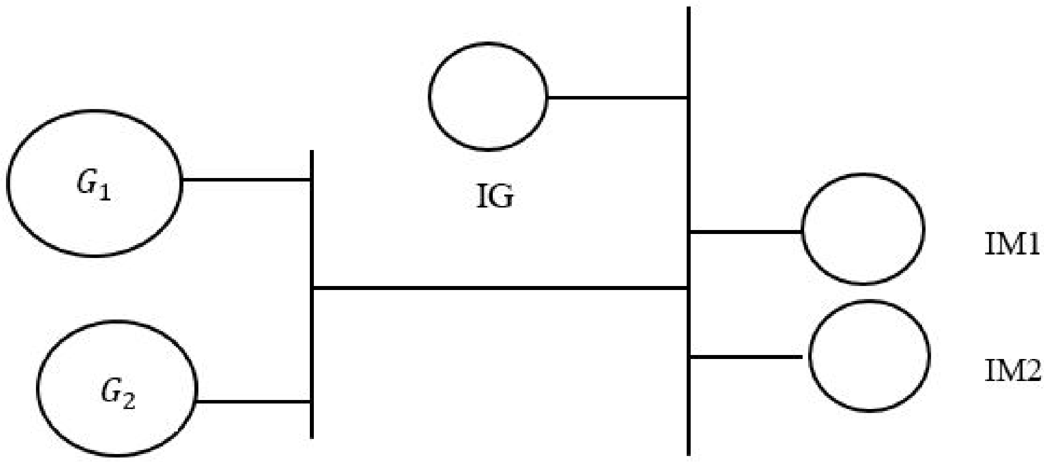

Figure 8. The power system single line diagram

According to [3], the synchronous generators oscillate against the induction motors. Through this model, which is done using SIMULIK tool in MATLAB, this is actually happened. Besides, they are oscillating against the induction generators. Figure (9), illustrates all the machines rotors speeds as an indication for their performance during a simulated model lasts for 10 seconds.

The upper line represents the rotor speed of the induction generator. The middle lines consists of two lines representing the rotors speeds of the two synchronous generators. While the lower line is actually consists of two lines of the rotors speeds of two induction motors. This model proves that the natural frequency of these different types of machines, connected together in a power system, is never intersect together [3]. This guarantees stability for this power system.

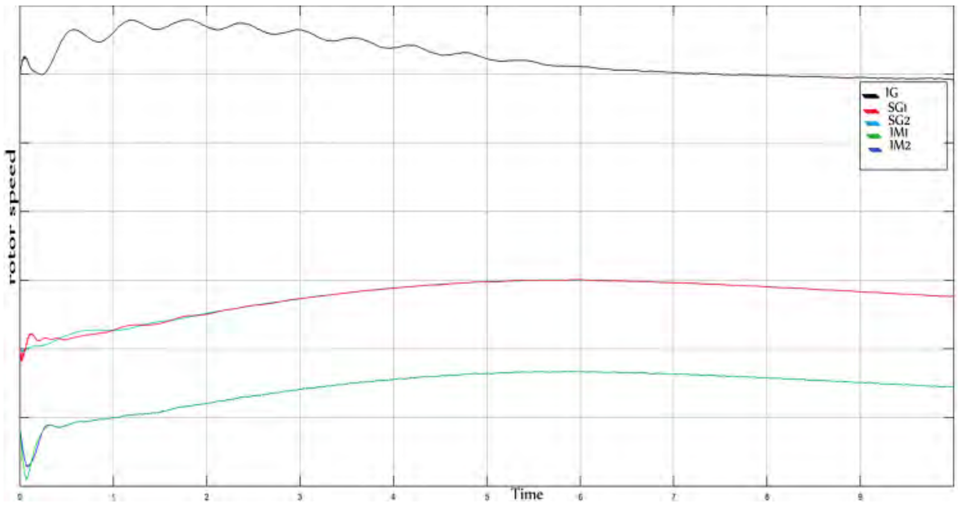

Figure 9. Rotors speeds of all machines in the system

6. Factors affecting natural frequency for induction motors:

There are many factors can affect the natural frequency of the induction motor. The inertia of the rotor, and the armature resistance have a remarkable effect in the damping of the transient oscillations during any perturbation affects the motor operation [4].

Figure (10) represents a power system consists of two induction motor connected in parallel to an infinite network:

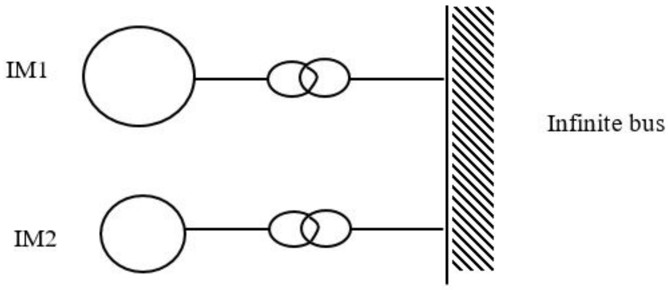

Figure 10. Two IM connected to infinite bus

For the first induction motor (IM 1), the rated power is 3000 HP, its stator resistance is 0.029 ohm and its inertia is 100.87Kg.m^2. As for the second one (IM 2), its rated power is 150 HP, its stator resistance is 0.01117 ohm and its inertia is 30.87 Kg.m^2. The system is analyzed during connecting both of these induction motors to the grid which is called direct on-line starting.

The resulted free oscillations during connecting the motor to the system are illustrated in Figure (11).

The blue line represents the oscillations of the rotor of the first motor, while the red line represents the oscillations of the rotor of the second motor.

According to [3], an induction motor with great slip has increased damping to the free oscillations during its transient period.

The slip effect is neglected in (6). For the induction motor mentioned earlier with natural frequency equals 3.3 cps, would completely lose its oscillations with this frequency if it has a slip equals:

$$S_0 \geq \sqrt{\frac{4v_1}{wT_a}} \tag{8}$$

which equals 3.5 per cent.

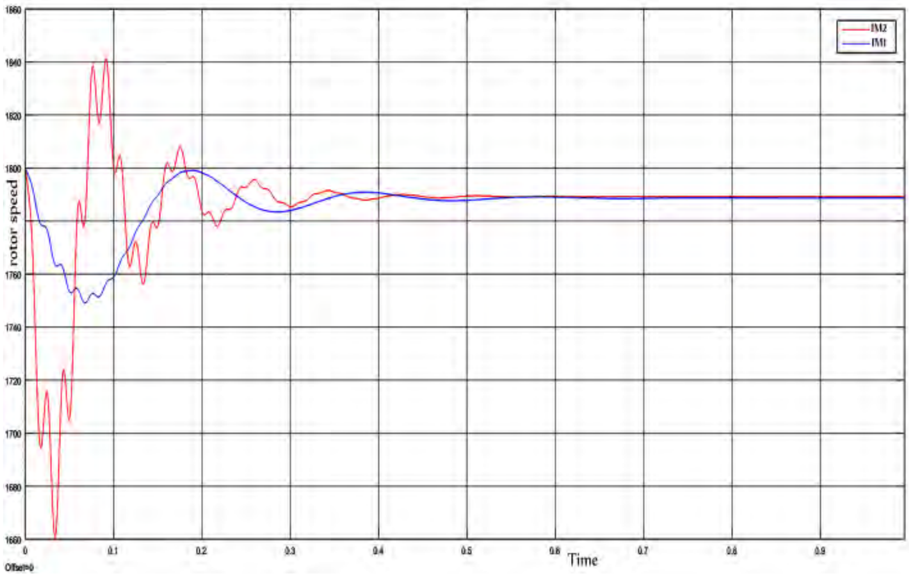

Figure 11. Rotors speeds of two IM connected to grid.

7. Induction motor under sudden changes:

For more analysis of the induction motor dynamics, the following system is considered. The same system at Figure (9) is restudied while disconnecting (IM 2) for 0.1 second. This sudden disconnection of (IM 2) causes a transient behavior by this motor trying to reach the steady state again. The rotors speeds during this sudden change is presented in Figure (12). This simulation lasts for 10 seconds describing the motor behavior during the start, disconnection and reconnection to the power system again.

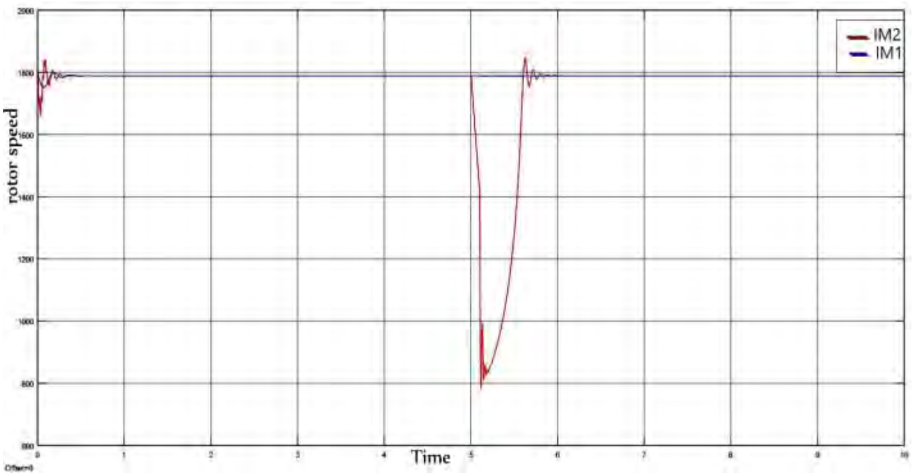

Figure 12. Rotors speeds during fault

The rotor speed of the second induction motor decreases suddenly then recovered again after successful damping of the resulted oscillations [5]. During this switching transient, the air gap torque increases. Besides, high inrush current flows in the second induction motor causes a voltage dip across its terminals. This causes the instantaneous slow down of the rotor speeds. It affects the voltage across the terminals of the healthy motor. Figures (13) and (14) show the voltage dips across the two machines:

8. Estimation of the induction motor natural frequency:

The dynamic analysis and testing of a three phase induction motor helps to estimate the main parameters of the motor such as the natural frequencies, damping ratios and the motor masses [6]. To determine the natural frequency of the induction motor, a mechanical test is widely used and it is called " the hammer impact method". In this test, three different parts are tested, the motor frame, the stator and its rotor. The response of each part is monitored and analyzed. The responses of the three parts are completely different. The results in time domain are recorded. This helps in avoidance of coincidence of the natural frequency of the motor with magnetomotive forces frequencies. This coincidence may generate electromagnetic noise which affects the motor behavior during sudden vibrations. The main target of this analysis is reaching for a quite operated steady motor. The measuring test system is shown in Figure (15)

The vibration response is measured in this test by using this impulse hummer to hit the illustrated system in a radial position. The errors of calculated results of the natural frequencies have to be within 2% of the experimental results [7]. These results must be useful during design phase to minimize noise and vibrations of induction motors.

9. Induction motor speed control:

Many applications for induction motors require an adjustable wide range of speeds. This leads to a huge development in AC adjustable speed motors. There are two ways to change the synchronous speed of the induction motor:

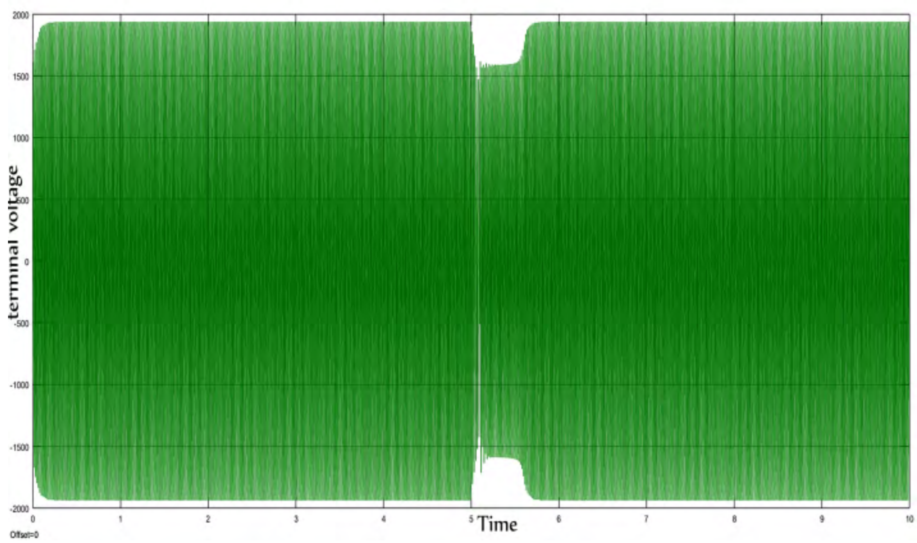

Figure 13. Voltage dip across IM2

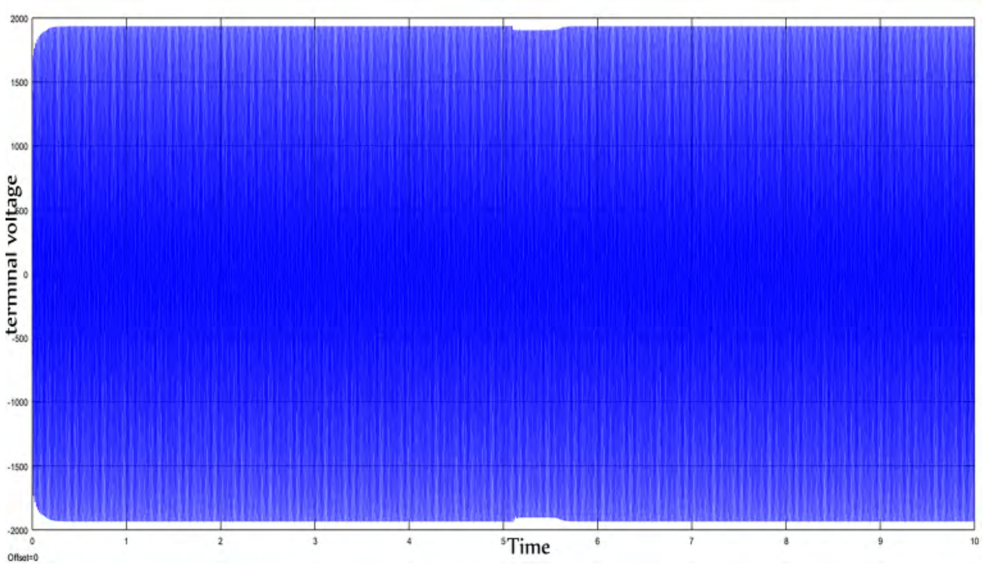

Figure 14. Voltage dip across IM1.

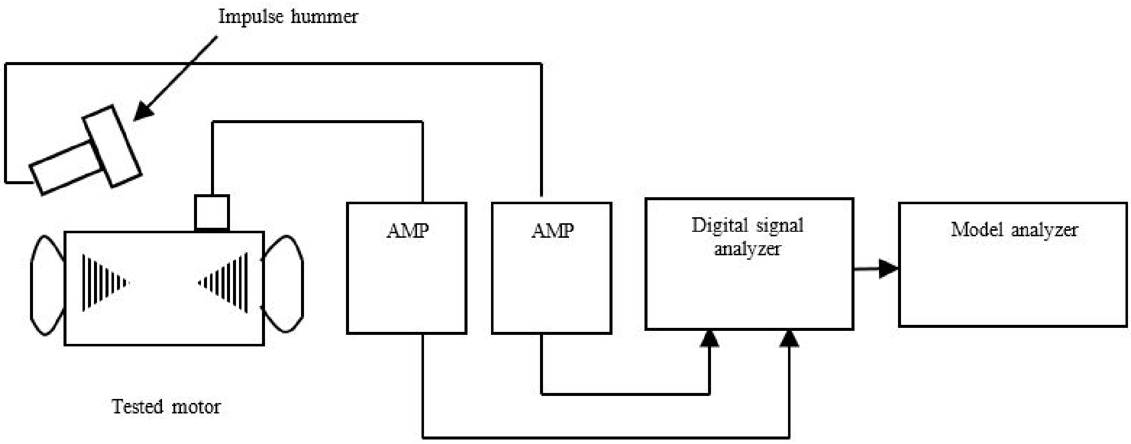

Figure 15. Parameters measurement system for IM

(i) to vary the poles numbers, and (ii) to change the line frequency.

As for the first method, the stator windings are designed to allow changes in the connections of the coil construction to change the poles number. In most cases, the rotor is going to be of a squirrel cage type. The main idea of the cage winding design, is to produce a rotor field with the same poles numbers of the inducing stator field. However, for the wound rotor design, it is more complex. As it is not only the stator windings are rearranged, the rotor windings have to be rearranged as well to change the pole number. For the second method, controlling the speed of the motor is done through changing of the line frequency. The line voltage is directly changes with the line frequency to keep constant flux density. The main factor affects this method, is to provide an effective source to have adjustable frequency. Nowadays, an induction motor with a wound rotor is used as a frequency changer or using " solid-state" frequency converters [8].

10. Conclusion:

This work discusses with many models the transient performance of induction motors in power systems. Through simple simulation of different induction motors models, an accurate prediction of its behavior and calculation of its natural frequency can be obtained. The response in these models is close to the mathematical formulas and theories about this dynamic performance. These models can cope with different conditions to provide an accurate simulation for induction motor in a power system. According to the given formulae and the simulation models, the natural frequency of the induction motor is higher compared with the synchronous generator. As a result, the damping of the transient oscillations has to be taken into consideration.

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