Modeling and analysis of energy losses under transient conditions in induction motors

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ABSTRACT

The present study is mainly concerned with solving the problems associated with energy losses resulting from starting transient conditions. In the present study, the possibilities of decreasing starting transient condition energy losses are investigated. Additionally, a comparison of the energy losses using different starting methods is also conducted. In this work, a complete description for deriving the equations used to calculate energy losses, mathematical analysis of the energy losses, the models of the different methods in this work were simulated using MATLAB/Simulink; and the results of energy losses and the dynamic characteristics are provided. Simulation results showed that the minimum starting energy losses were accomplished by soft starting method, in which the starting current could be reduced to the minimum value.

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1. INTRODUCTION

Energy conversion, in induction motors (IM), is obtained by the induced current in the rotor windings produced by electromagnetic induction [1]. The IM has three operation modes: generator, motor and electromagnetic brake and it is well known that the each of IM current, torque, slip and speed vary according to the load connected to the motor [2], [3]. The rotor speed is zero at starting time. A very large starting current is generated in the rotor windings causing the motor stator current to increase 7 to 10 times the rated current value. The value of the starting current should be limited since too large starting current will cause many adverse effects. Reducing the stator winding supply voltage when the motor starts is the common way to reduce the starting current. However, it should be noted that reducing power supply voltage in order to decrease the starting current, will also reduce the starting torque even further, which will affect the starting performance of the motor. With increasing the motor speed, the speed of the stator's rotating magnetic field is reduced, and the current in the rotor windings is also reduced, so when the motor reaches its rated speed, the stator winding current is reduced to a smaller value; reaching its rated current value [4], [5]. Due to the high starting current in the IM, the windings of the motor can be burned due to overheating, especially if the load is heavy; the IM isn't capable of reaching its rated speed in a short time window, another scenario is that the motor will rotate forward and reverse, which will cause overheat of the motor windings, and then the motor windings will burn due to overheating [6]–[8].

The second main problem in IM caused by high starting current is the high energy losses during the starting process the energy losses however, are proportional to the square of the starting current. Especially that many IMs that are used in industry apply the operation mode of "start-stop" regimes like lifts and pumps [9], [10]. It should be noted that in developing countries, like Jordan, Industry cannot afford the high energy costs correlated with reducing the starting energy of IM [11]–[16]. There are several methods to reduce energy losses in IM such as: rotor design (RD), frequency control (FC), resistance of the rotor (RR), soft starter (SS) and voltage steps control (VSC) [17], [18]. In the last method, the step wise raise in the applied voltage during the starting process will reduce the energy losses, and the observed decrease in energy losses will greatly depend on the number of steps for voltage rising steps [19]. In the current work, two methods will be investigated and compared not only for decreasing the energy losses of IM, but also compared to the previously applied methods used for decreasing energy losses for separately excited DC motors [20]–[23]. These two methods include soft starting and multi-step voltage rising methods.

2. RESEARCH METHOD

The analysis of energy losses at the starting of IM without load [24], [25]:

$$T_L = 0$$

$$T_m - T_L = J\frac{d\omega_m}{dt}$$

$$S = \frac{\omega_0 - \omega_m}{\omega_0}$$

$\omega = \omega_0(1-S)$ and, $d\omega = -\omega_0\frac{ds}{dt}$

which may be written as (1):

$$dt = -\frac{J\omega_0 ds}{T} \tag{1}$$

where, T is motor torque [n.m], T_L is load torque [n.m], J is moment of inertia [Kg/m2], ω_m is mechanical angular velocity [rad/s], ω_0 is synchronous angular velocity [rad/s], and S is slip of motor. The energy losses in machine are calculated by applying:

$$\Delta A_{str} = \text{Stator Losses} + \text{Rotor Losses} + \text{Mechanical Losses} + \text{Iron Losses}$$

where, $P_{stator\ losses} = 3 * I_1^2 * R_1$ and $P_{rotor\ losses} = 3 * I_2^2 * R_2$. The iron and mechanical losses will be neglected due to their small values.

$$\Delta A_{str} = \int_0^{t_{str}}((3 * I_1^2 * R_1) + (3 * I_2^2 * R_2))dt \tag{2}$$

The influence of the no-load current can be neglected, and then:

$(I_1 = I_{nL} + I_2)$ and finally $(I_1 = I_2)$

$$\Delta A_{str} = \int_0^{t_{str}}(3 * \mathrm{I}_2^2 * (\mathrm{R}_1 + \mathrm{R}_2))\mathrm{dt} \tag{3}$$

$$\Delta A_{str} = \int_0^{t_{str}}\left(3 * \mathrm{I}_2^2 * \mathrm{R}_2(1 + \frac{\mathrm{R}_1}{\mathrm{R}_2})\right)\mathrm{dt} \tag{4}$$

Substituting (1) in (4) gives (5).

$$\Delta A_{str} = \int_0^{t_{str}}(3 * \mathrm{I}_2^2 * \mathrm{R}_2(1 + \frac{\mathrm{R}_1}{\mathrm{R}_2}))(-\frac{\mathrm{Jwods}}{\mathrm{T}}) \tag{5}$$

The equations used for determining power losses are:

$$P_{conv} = T * \omega_m$$

$$(1-S)P_{a.gap} = T * (1-S)\omega_0 \tag{6}$$

$$P_{a.gap} = 3 * I_2^2 * \frac{R_2}{S} \tag{7}$$

as shown in (6) and (7) give:

$$3 * \mathrm{I}_2^2 * \mathrm{R}_2 = \mathrm{T} * \omega_0 * \mathrm{S} \tag{8}$$

as shown in (5) and (8) give:

$$\Delta A_{str} = -\int_{S_{in}}^{S_{yn}} \left(J\omega_0^2 + JW\omega_0^2 \frac{R_1}{R_2}\right) s.ds \tag{9}$$

which may be written as (10):

$$\Delta \mathrm{A}_{\mathrm{str}} = \int_{\mathrm{S_{yn}}}^{\mathrm{S_{in}}} \left(\mathrm{J}\omega_0^2 + \mathrm{J}\omega_0^2 \frac{\mathrm{R}_1}{\mathrm{R}_2}\right) \mathrm{s.ds} \tag{10}$$

where ΔA_{str}: total starting losses; I_1: stator current; I_2: rotor current; R_1: stator resistance; R_2: rotor resistance; P_{RLs}: power losses in rotor through the slip power. When the motor starts-up from standstill (Sin=1), to the synchronous speed (Syn=0).

$$\Delta A_{str} = \int_0^1 \left(J\omega_0^2 + J\omega_0^2 \frac{R_1}{R_2}\right) s.ds \tag{11}$$

After integration, (11) will be as:

$$\Delta A_{str} = (J\omega_0^2 + J\omega_0^2 \frac{R_1}{R_2}) * (\frac{s^2}{2}), \quad [1 \text{ to } 0] \tag{12}$$

$$2\, \Delta A_{str} = \frac{1}{2}(J\omega_0^2 + J\omega_0^2 \frac{R_1}{R_2}) \tag{13}$$

where, $\frac{1}{2}\, J\omega_0^2$ is the losses in the rotor circuit and $\frac{1}{2}\, J\omega_0^2 \frac{R_1}{R_2}$ is the losses in stator circuit.

Here it is very important to notice that the kinetic energy stored in moving parts of the machine is equal to the machines' rotor winding energy loss. From the above analysis of energy loss equations, it is clear that the stator electrical losses in transient condition depend on the resistance of the rotor circuit. With the stator resistance invariable. This shows that the increase in rotor resistance causes a decrease in stator electrical losses, $\Delta A_{str} \propto \frac{1}{R_2}$.

3. RESULTS AND DISCUSSION

MATLAB/Simulink is a very useful tool for simulating and modeling IM and predicting their dynamic behavior. In this model the IM, power supply, equations and results of energy starting losses are presented in special blocks of Simulink library. This model is suitable to simulate different methods of starting and helps to conclude which one of them is the best this paper investigates the direct, multi-step, and soft starting methods.

3.1. Voltage variation law

Using MATLAB/Simulink different models of induction motor are studied to investigate the energy losses in this motor, these models differ from each other just in the method of supplying voltage. In the first case voltage is supplied directly, in the second case it is supplied in multi-step rising method and in the last one it is supplied with linear rising method. In this paper is presented the last one model but the results of losses of each model is presented down in Tables 1, 2 and 3.

Figure 1 show the MATLAB/Simulink simulation of an alternating current (AC) motor model during a linear rising voltage. Figure 2 show the MATLAB/Simulink simulation results of the voltage-current power supply of an AC motor during a linear rising voltage. Figures 3 and 4 show the relationship of the induced torque and the motor speed of an AC motor during a linear rising voltage, as obtained by the simulation of the MATLAB/Simulink program. Simulation results clearly indicated that the starting current could be controlled to a value that minimizes the losses in the motor by using linear rising voltage starting method. The results showed that after a transient condition period, the torque and the speed of the motor were close to the rated values, and the speed was changing smoothly.

Table 1. The starting current at different voltage control method

Normal starting		With multi step raising voltage	With linear raising voltage	
Voltage source, V	Starting current, A	Starting current, A	Starting current, A	Steady stat current, A
A		27.6	13.4	7.4
400	61.12	26.2	12.7	6.8
380	58.00	16.5	8.0	4.3
240	36.60	15.3	7.3	3.9
220	33.50	13.7	6.7	3.5

Table 2. The electrical losses resulting from the starting current

Voltage source, V	Direct starting losses, kW	Multi-step rising losses, W	Linear rising losses, W
400	3.2	1000.0	252.0
380	2.8	964.0	226.6
240	1.8	382.5	89.9
220	1.5	328.9	74.8
200	1.3	263.7	63.0

Table 3. The electrical losses resulting from resistance control

	At R1=0.5968 Ω, R2=0.6258 Ω	
psl=1327.0	psrl=679.5	Pssl=648.0
	At R1=0.9 Ω, R2=0.6258 Ω	
psl=1657.0	psrl=679.5	Pssl=977.2
	At R1=1.2 Ω, R2=0.6258 Ω	
psl=1982.0	psrl=679.5	Pssl=1303.0
	At R1=0.5968 Ω, R2=0.9 Ω	
psl=1130.0	psrl=679.5	Pssl=450.0
	At R1=0.5968 Ω, R2=1.2 Ω	
psl=1017.0	psrl=679.5	Pssl=337.9

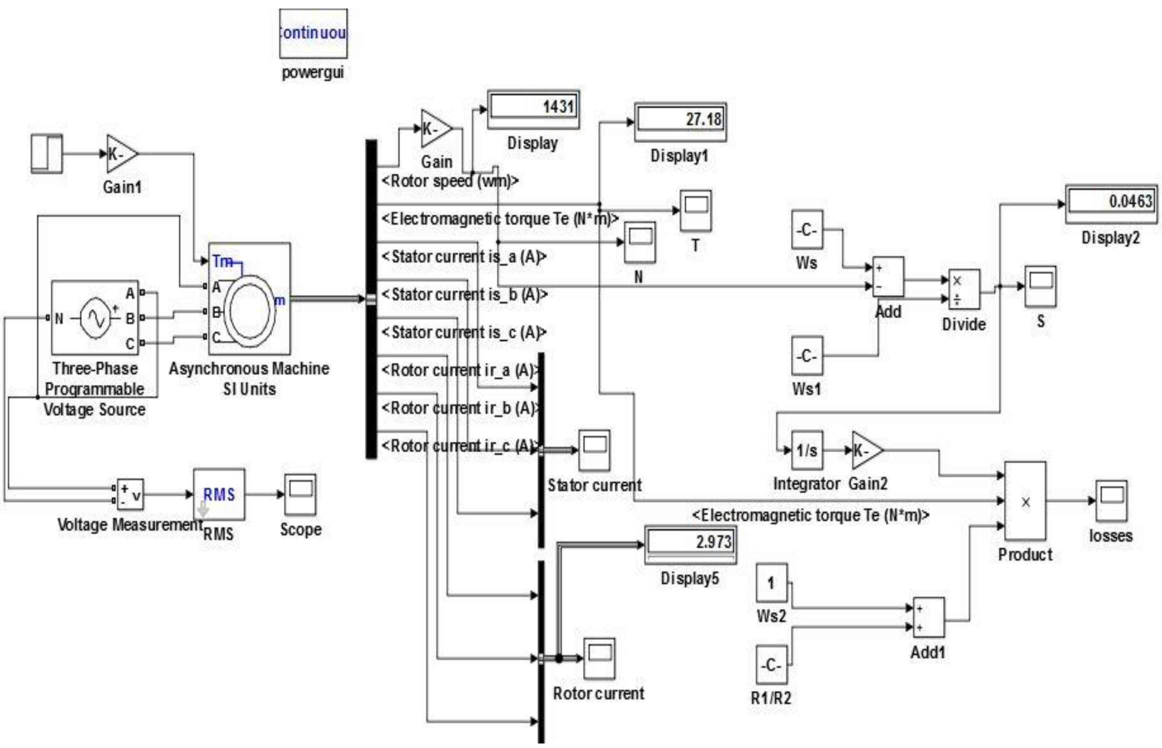

Figure 1. Soft starting Simulink model

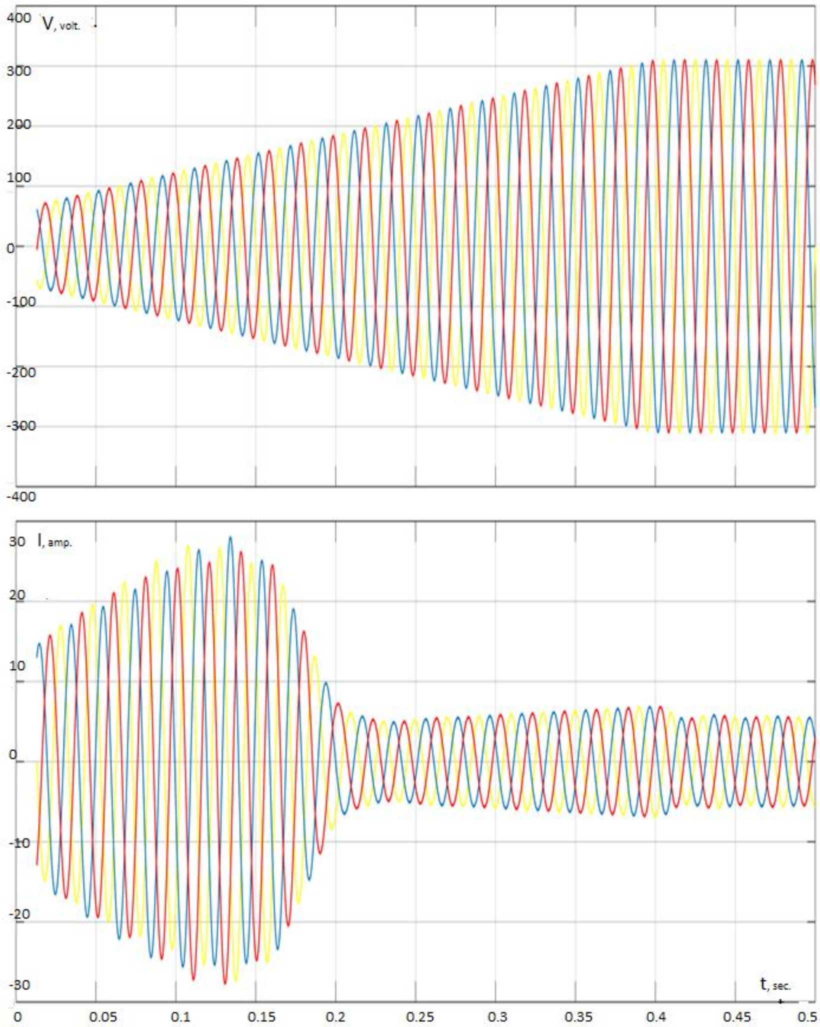

Figure 2. Soft starter, (voltage-current) characteristic

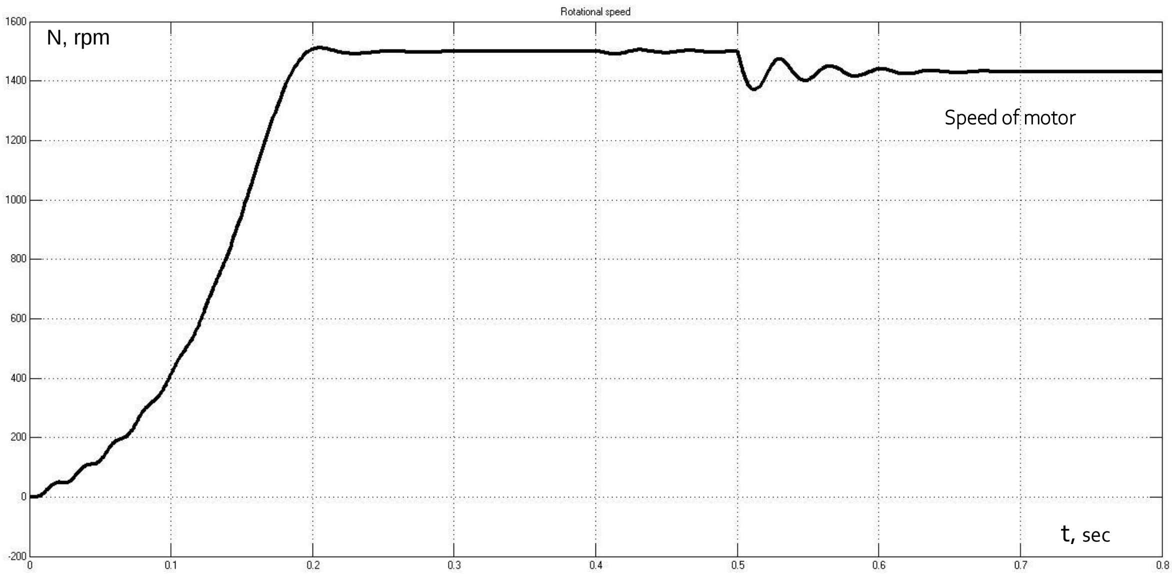

Figure 3. Soft starter, mechanical speed characteristic

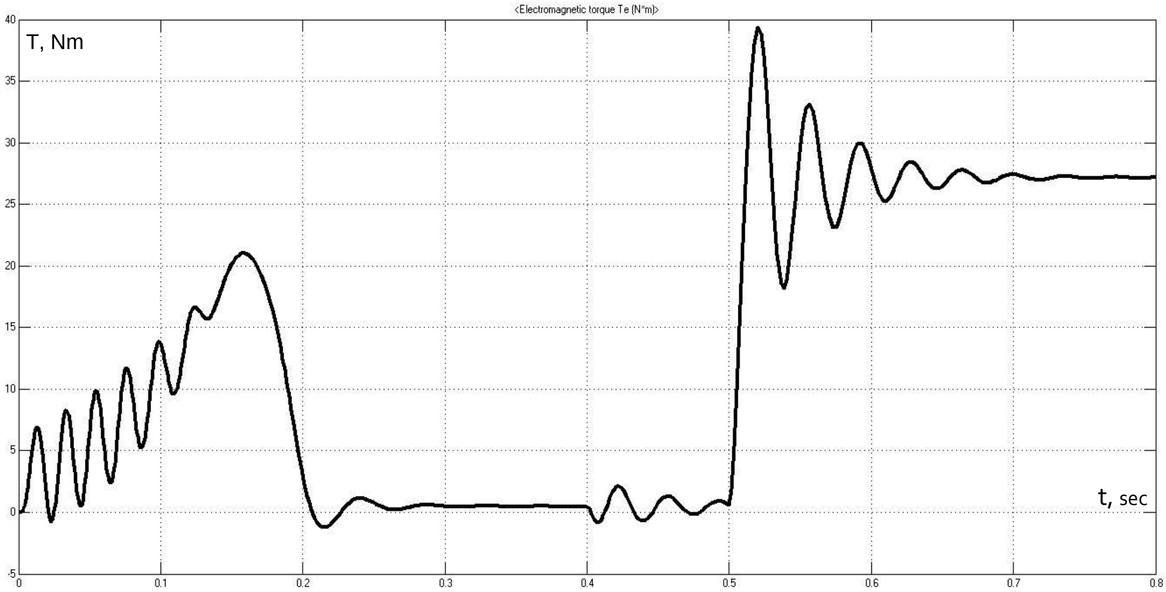

Figure 4. Soft starter, torque characteristic

4. RESULTS OF ENERGY LOSS SIMULATION MODELS

4.1. Starting current at different voltage control method

Table 1 shows the electrical losses of starting current by using different starting methods, direct starting, multi-step voltage law and soft starter-linear rising voltage law as a function of firing angle. From the Table 1 it is seen that the best way to decrease the starting current is by using the soft starting by which the voltage is supplied in a linear rising method. It is also seen that maximum currents are obtained in a direct starting method.

4.2. Stator cupper loss at a different voltage control method

As shown in the Table 2, the electrical losses resulting from the starting current will decrease. It was found from the results that the starting current decreases greatly using the soft starter-linear rising voltage law-, as changing the firing angel with time makes the current increase in a smoother manner until it reaches its rated value. It is also seen that the maximum energy losses are obtained in a direct starting method in which the rated voltage is supplied directly in one step.

4.3. Results of resistance control simulation model

Table 3 shows the investigation and results of the electrical losses and their proportionality with resistors R1 and R2 and has showed the effect of using this method to reduce the electrical losses where, Pssl-steady state losses; prl-rotor windings losses and psl-stator windings losses. It is noticed from the previous results and the above equations that the electrical losses are directly proportional to R1 and inversely proportional to R2. The equations clarified that the resistors R1 and R2 did not affect the electrical losses in the rotor and displayed the inaccuracy of using this method to reduce the electrical losses, since it discards the effects of changing resistors on the speed of a rotor. However, it should be mentioned that this discard was governed by the fact that it affected the stability of motor running, knowing that the speed affects the value of electrical losses as shown in the equations.

5. CONCLUSION

From the used methods to reduce electrical starting transient conditions losses, minimum losses were achieved by using Smooth starter-linear rising voltage law, the second in order in efficiency was the control method of multi-step voltage rising and the least efficient was the direct starting method. And finally, the method of stator and rotor inserting resistors was found to be useless in reducing transient condition losses. The reason the smooth starter is the best method to be used is that the voltage feeds the motor gradually, which causes the motor to take off with a small starting current, so the losses resulting from the transient states decrease significantly.

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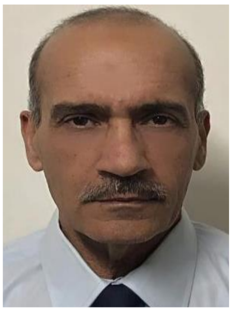

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