AN ANALYTICAL INVESTIGATION OF INDUCTION MOTOR BEHAVIOR IN THE CASE OF FLICKER OCCURRENCE USING FINITE ELEMENT METHOD

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This paper investigates induction motor modeling parameters and its behavior under flicker conditions using finite element method (FEM). Nowadays, increasing usage of power electronics and harmonics-made loads has made power quality a challenging issue. Therefore, the behavior of electrical elements (e.g. motors), under the power quality conditions, needs to be studied. Despite definite induction motor's parameters, there are several defeats in the modeling procedure of the motor. Considering all of the parameters of the motor, it may make the analysis complicated incongruously. To ease the problem, numerical methods is employed. In this paper, an induction motor is modeled completely. The machine is modeled by 2D method and the effect of excitation system is seen. The effect of the motor winding is studied, and the results are compared with other models. In order to earn accurate results, some modifications in 2D modeling are applied. The motor is subjected to flicker condition. All of obtained results are simulated by MAXWELL software.

Keywords: Induction Motor; Flicker; Power Quality; FEM

1. Introduction

Nowadays, the increasing growth of demand for power electronics and other non-linear electrical components has led to a major issue called power quality [1]. Power quality is one of the important challenges in the context of power system and its elements. When an electrical element is exposed to flicker condition its input and output relation changes and its loss increases. Undoubtedly, for attaining meaningful results, accurate and perfect modeling of the elements is a must. Therefore, in order to study the case of power quality criterions such as flicker, the conventional models for the electrical elements should be modified. Specifically, for the analysis of induction motor under flicker condition, the classical model should be modified. In the line of related works, different approaches have been proposed in the literature [2-4]. In [2] and [3], small signal model has been used to analysis the effect of the flicker. A number of

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works have been performed in frequency-domain flicker assessment [11], [12]. Our research interest is put on studying the offline frequency domain IEC flicker meter that works on the fast Fourier transform (FFT).

In [4] an equivalent circuit for analysis of induction motor in the presence of the flicker has been suggested, where the modified model consists of three sub-models. Therein, it concluded that total behavior of the motor is equal to the sum of the three sub-models. This rest of this paper is organized as follows. In the section II, the need for analysis of the motor in the presence of the flicker is addressed. In the section III modeling procedure of induction motor in MAXWELL software is presented. The considerations must be noticed in the modeling for accurate results are discussed in this section. Section IV deals with the simulation results for three types of motor winding. The variation of motor parameters such as output power, input current, rotor speed and motor loss and harmonic analysis are studied. Finally the section V concludes this paper.

2. Problem Definition

Models developed for induction motor are based on the consistency of input voltage frequency. Usually, motor parameters are defined in network and slip frequencies. Such models are not suitable for the study of the power quality. In such studies, the input frequency is not the same as the network frequency (50 or 60 Hz) and the usual models of the motor cannot be applied. Experiments show that in the presence of the flicker, the loss of motor increases, and motor speed deviates compared to the case where there is no flicker. Dynamic analysis is a powerful tool for the investigation of the motor performance in such situations. So, transient study in MAXWELL software has been deployed in order to analyze motor behavior under flicker conditions. In [4] a model for induction motor is developed that has three sub-models:1) network frequency (w_b) sub-model 2) lower frequency ($w_b - w_m$) sub-model 3) upper frequency ($w_b + w_m$) sub-model. This model suffers the lack of the effect of the induction motor winding and its structure. This paper presents the analytical study of the induction motor behavior in the presence of the flicker. The effect of the induction motor winding has been investigated using MAXWELL software. The change of output power, speed, loss and other parameters has been discussed when the input voltage has flicker. The software used in this paper is MAXWELL 14, as it provides transient study as well as fast and accurate simulations.

3. Problem Modeling

3.1. Motor parameters

In this paper a 110-kilowatt (150 HP) motor is considered. Table 1 presents the motor parameters. There are two approaches for the modeling of the motor in MAXWELL, namely 3D and 2D. Since the former approach is capable of considering end winding edges, it has high level of accuracy [5, 6]. However, it suffers from high computational cost. Although, in the latter approach, some parts of motor are neglected. But, it has less computational cost, and it is suitable for this study. The effect of end winding the edge and its impedance as well as inductance will be taken into account. Although solving the problem using numerical methods such as FEM take more time, it is necessary for trustable results [7]. Almost all of electrical motors have laminate cores, to reduce eddy current effect. Laminating the core blocks the eddy current. In 2D modeling, the conductivity of core is considered to be equal to zero [8, 9].

Table 1

Motor parameters

Parameter	Value	Parameter	Value
Nominal Power	100 KW	Rotor Outer Diameter	111.6 mm
Number of Stator Slot	24	Stator Connection	Delta
Number of Rotor Slot	31	Air Gap	1.2 mm
Stator Outer Diameter	210 mm	Motor Length	980 mm
Stator Inner Diameter	114 mm	Nominal Voltage	3-phase 380 V
Stator winding: Concentric double layer winding Number of Conductors per slot: 12			

3.2. Motor Excitation Modeling in the presence of flicker

There are two methods for the excitation in MAXWELL. One is utilization of voltage source, and the other is utilization of the current source. When using current source as an excitation system, there is no need for the dynamic of the excitation system and its circuit. In this excitation method, the connection type between slots is not important. It only needs the current density in every slot. This method is used when the purpose of simulation is analysis of the motor in a specific current. Furthermore, it can be used to calculate motor current in different slips; this current is then fed to the excitation system [10]. Clearly, this method has a large error. As, the purpose is studying the dynamic behavior of the motor, this method is not a good approach. Thus, in order to see the dynamic behavior and circuit structure of excitation system and the effect of winding type on the motor, voltage source method is applied. Excitation circuit modeling is explained in [11, 12].

In 2D modeling, the resistance and inductance of winding located out of the slots are not considered. Neglecting these winding resistance and inductance will cause large errors. That must be taken into consideration throughout 2D modeling.

For modeling the effect of the out of the slot winding resistance, this resistance should be calculated and added to the effective resistance of winding in stator. In voltage source excitation model, the resistance of stator winding must be entered in the model, directly. Knowing the length and dimension of the winding, the resistance of stator winding can be calculated. The out of the slot winding inductance effect can be calculated, using the equation below [13]. This amount can be added directly in the excitation model:

$$X_0 = 8\pi f\left(T_{ph}\right)^2 l_0\left(\frac{\lambda_0}{qP}\right), \quad (1)$$

where $l_0$is the length winding located out of the slot, T_{ph} is the number of the turns per phase, q is the number of slot per pole, P is the number of poles; moreover λ_0 is defined as follows:

$$\lambda_0 = \frac{\mu_0 K_s \tau^2}{l_0 \pi Y_s}, \quad (2)$$

where K_s is slot leakage factor (almost equal to unity.), Y_s is slot pitch, and τ is pole pitch. In the situation where flicker is present, the input voltage in the excitation model is given by [11]:

$$v(t) = V_p(1 + k\sin w_m t)cosw_b t \quad (3)$$

This input voltage can be rewrite as:

$$\begin{aligned} v(t) &= V_p(1 + k\sin w_m t)cosw_b t \\ &= V_p cosw_b t + V_p k cosw_b t \sin w_m t \\ &= V_p cosw_b t + \frac{V_p k}{2}\sin((w_m + w_b)t) - \frac{V_p k}{2}\sin((w_m - w_b)t) \end{aligned} \quad (4)$$

In (4) w_b is the network (fundamental) frequency, w_m is modulating (flicker) frequency, V_p is the line to neutral voltage, and k is the modulating depth. In this paper the modulating depth is assumed to be equal to 0.01, and the flicker frequency (f_m) is equal to 10Hz. The simulated machine with specified parameters in Table 1, can be seen in Fig.1.

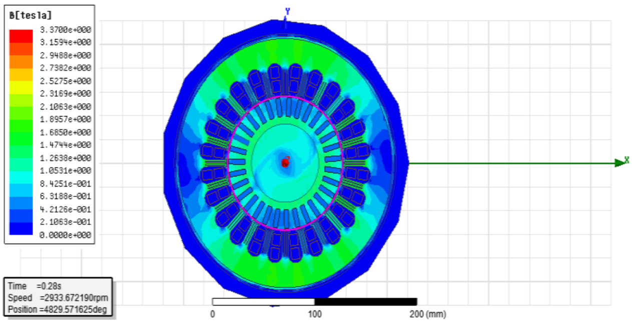


Fig. 1: The simulated machine in MAXWELL software.

4. Simulation results

The motor analyzed in this paper is modeled with three winding types. These winding types have different coil pitches i.e. 2/3 pitch, 5/6 pitch and full pitch winding. Fig. 2 shows motor output power in the presence and absence of the flicker. According to Fig.2, when input voltage has no flicker, the output power settles at a constant power (about 100kW). When the flicker with 10Hz and 10% amplitude is present, the output power has fluctuation over 100kW with maximum amplitude of 625W. The FFT of output power is shown in Fig.3.

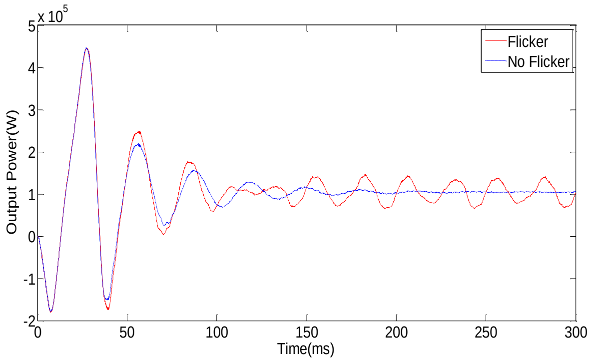
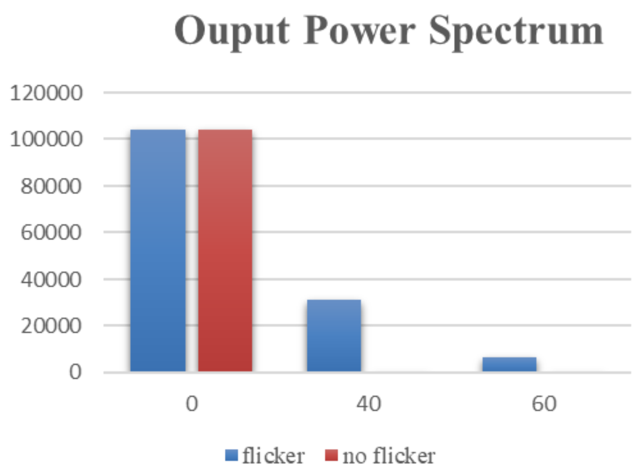


Fig. 2: Motor output power in the presence of flicker (lined diagram) and absence of flicker (dotted diagram) for full pitch winding

As it is expected, the output power has 2 more harmonic terms in 40Hz and 60Hz. Fig. 4 represents the motor torque for full pitch winding. It is clear that motor torque has to swing over its previous value (about 350 N.m in the absence of the flicker). Similar to the output power, motor torque has 2 more harmonic terms in 40Hz and 50Hz. The variation of speed is plotted in Fig.5. As Fig.5 shows, similar to the output power, speed has fluctuations over the previous speed of the motor (in absence of the flicker). This speed swing can be explained using output power diagram and motor torque equation, i.e.:



$$T_m - T_l = J\frac{dw}{dt}. \qquad (5)$$

Fig. 3: FFT diagram of output power in presence and absence of flicker for full pitch winding

The FFT of output power (W)

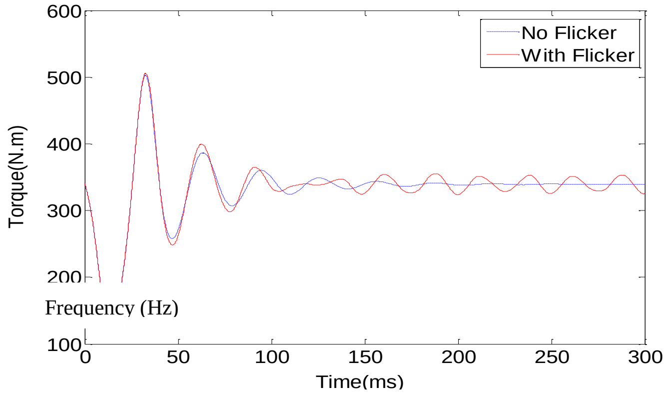


Fig. 4: Motor output Torque in the presence of flicker (lined diagram) and absence of flicker (dotted diagram) for full pitch winding

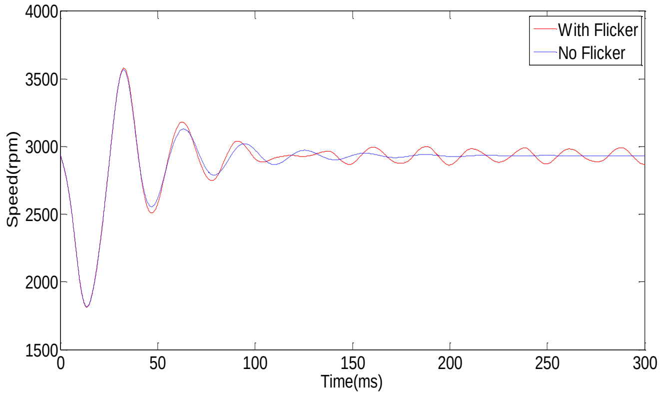


Fig. 5: Motor speed in the presence of flicker (lined diagram) and absence of flicker (dotted diagram) for full pitch winding

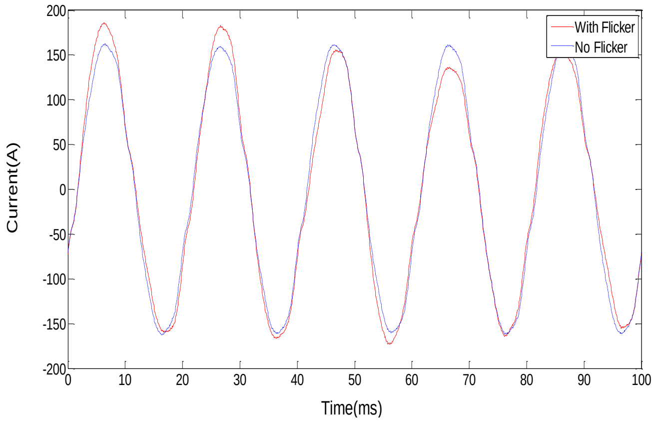


Fig. 6: Motor input current in the presence of flicker (lined diagram) and absence of flicker (dotted diagram) for full pitch winding

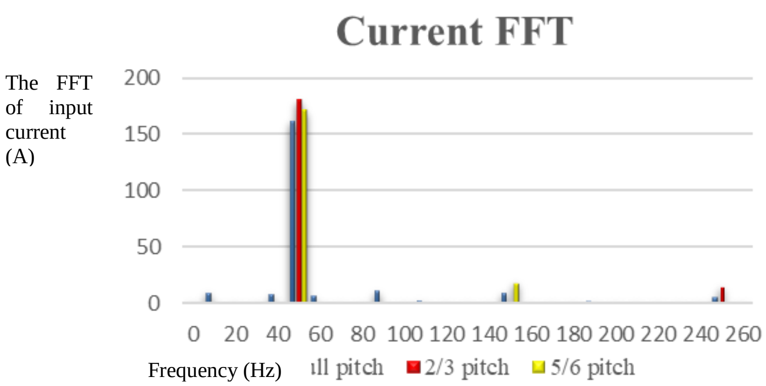


Fig. 7: FFT of input current in presence of flicker for three winding types

Referring to the output power diagram in Fig. 2, in a half cycle where the output power exceeds its base power (in absence of the flicker (100kW)), the speed will accelerate from its base speed (in absence of the flicker (3000 rpm)). Furthermore, in a half cycle where the output power is less than its base value, there is a braking period. Fig. 6 illustrates the motor input current for the full pitch case. It is clear that current has the flicker. The FFT diagram of input current for all different cases in the presence of the flicker is shown in Fig.7.

It should be noted that, in fractional winding such as 2/3 pitch and 5/6 pitch, the 50Hz harmonic of current is greater than the full pitch winding. This can be explained using motor input current equation, i.e.:

$$i = \frac{v-e}{z} \tag{6}$$

where *e* is the induced voltage in the motor and is defined as below:

$$e = K_w \times 4.44Nf\varphi\ . \tag{7}$$

in which, K_w is the winding factor. This factor is equal to the product of pitch factor K_p and distribution factor K_d.Winding factor is equal to unity for full pitch winding. For fractional winding, this factor is less than unity. In fractional winding, because winding factor is lower than full pitch winding the induced voltage in motor decreases and the amount of current increases. The other point should be mentioned here is that, fractional winding eliminates some harmonics. Using fractional winding with the fractional value of $1-\frac{1}{n}$ will eliminate the n'th order harmonic of the motor. This is proved in the appendix. Fig.6 shows that for the 2/3 pitch winding, the harmonic content of the third harmonic (150Hz) is less than the other sorts of winding. For 5/6 pitch winding, the harmonic content of 5'th harmonic (250Hz) is less than the others. Motor loss and efficiency for all of the mentioned cases are brought in table 2. It can be seen from table 2 that in the presence of the flicker, motor loss increases, and its efficiency decreases.

Table 2

Motor loss and efficiency for three types of winding, with and without flicker

Winding Types			Parameters	
Coil Pitch=$\frac{5}{6}$	Coil Pitch=$\frac{2}{3}$	Full Pitch		
9246	23138	8358	Loss(W)	Without Flicker
91.89	89.28	93.33	$\eta(\%)$	
9782	23239	9359	Loss(W)	With Flicker
90.37	88.02	92.67	$\eta(\%)$	

In the 2/3 pitch type, due to largeness of input current, motor loss is the worst (owing to ohmic loss). Fig.8 shows motor loss harmonic content. It should be noticed that the difference between the mean value of loss in presence and absence of the flicker is almost equal to the loss in lower and upper frequency sub-models (40Hz and 60Hz).

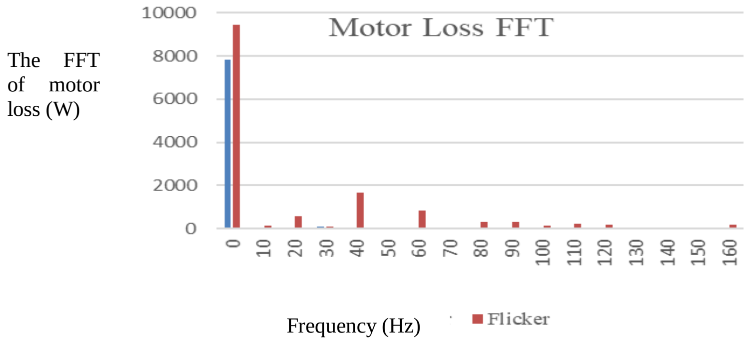


Fig. 8: FFT of motor loss in presence and absence of flicker for full pitch winding

At Last a comparison between the simulation result for the output power in MAXWELL and the proposed model in [4] is represented. The model represented in [4] is simulated via MATLAB/Simulink. As mentioned before; this model has three sub-models. The resultant behavior of the motor in flicker condition is equal to the summation of three sub-models. Fig. 9 illustrates the comparison between the model proposed in [4] (MATLAB) and the simulation in this paper (MAXWELL).

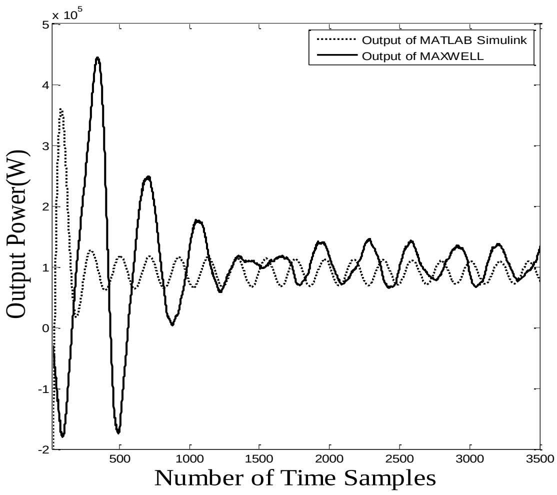


Fig. 9: Comparison between proposed model in [4] and MAXWELL simulations for full pitch winding

The simulation of the induction motor in MATLAB software is without considering the structure and the characteristics of the Induction motor core. It can be seen that considering the detailed model of the motor (slot shape, motor structure, winding type and so on) would make a phase shift in output power. The output power magnitude difference between the presented model in this paper and the model in [4] is very low. Fig.9 shows that modeling induction machine using FEM has more transient and the fluctuation frequency changes by the effect of winding slots and sub-harmonics. The ideal modeling by MATLAB is less transient than the complete simulation in MAXWELL.

5. Conclusion

This paper presents an analytical study of induction motor behavior on the condition of flicker occurrence using FEM. 110kW induction motor was modeled in MAXWELL software completely, using 2-dimensional modeling. Some modifications in the modeling were applied to earn accurate and trustable results. Afterwards, the motor was excited with an input voltage containing flicker. Motor electrical and mechanical parameters like motor speed, motor torque, input current, output power and motor loss was studied. The harmonic study shows that in flicker condition, induction motors can be seen as three induction motors excited with three frequencies. These three frequencies are network frequency (f_b), lower frequency ($f_b - f_m$) and upper frequency ($f_b + f_m$). The result of this model and complete simulation was compared. The effect of the motor winding type was seen, in the paper. Using fractional winding may cause some harmonics to be omitted. These winding types have major effect on motor input current, loss and efficiency. In Industrial plants using lots of motors, the start and stop of motors will cause power fluctuation and voltage flicker. The results show that the induction motor is sensitive to voltage flicker within certain amplitude levels and frequencies. As expected, the fluctuations of power, input current, Torque and speed are the same as the flicker frequency. The presence of Flicker in the induction motor voltage can cause power swing and limitation of operation of induction motor. This problem has more effects with increasing the number of induction motors.

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Appendix (winding and pitch factor)

Winding factor is defined as a product of distribution factor and pitch factor.

$$K_w = K_p \times K_d \quad \text{(A.1)}$$

Pitch factor is defined as the ratio of vector sum of induced voltage in coils of winding to arithmetic sum of induced voltage in coils of winding. This definition can be described by the figure below.

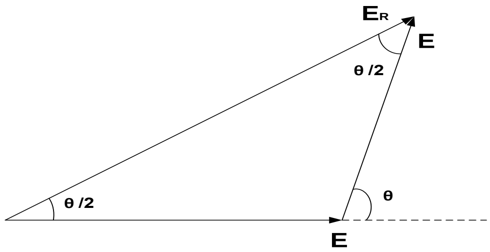

Fig. A.1: Induced voltage in coils

Pitch factor is defined as below:

$$K_p = \frac{2E\cos\frac{\theta}{2}}{2E} = \cos\frac{\theta}{2} \quad (A.2)$$

In which θ is chording angle. For the n order harmonic, pitch factor is defined as:

$$K_{pn} = \cos\frac{n\theta}{2} \quad (A.3)$$

If the winding is fractional with value of $1 - \frac{1}{n}$, then, chording angle is equal to:

$$\text{Coil pith} = 180^{\circ}(1 - \frac{1}{n})$$

$$\text{Chording angle} = \theta = 180^{\circ} - \text{Coil pith} = \frac{180^{\circ}}{n} \quad (A.4)$$

So, pitch factor for the n order will be equal to zero.

$$K_{pn} = \cos\frac{n\theta}{2} = \cos 90^{\circ} = 0 \quad (A.5)$$

For 5/6 pitch winding the 5'th harmonic content is low:

$$\text{Coil pith} = 180^{\circ} \times \frac{5}{6} = 150^{\circ}$$

$$\text{Chording angle} = \theta = 180^{\circ} - \text{Coil pith} = 30^{\circ} \quad (A.6)$$

$$K_{p5} = \cos\frac{n\theta}{2} = \cos\frac{5 \times 30^{\circ}}{2} = 0.25$$

For 2/3 pitch winding the 3'th harmonic content is omitted:

$$\text{Coil pith} = 180^{\circ} \times \frac{2}{3} = 120^{\circ}$$

$$\text{Chording angle} = \theta = 180^{\circ} - \text{Coil pith} = 60^{\circ} \quad (A.7)$$

$$K_{p3} = \cos\frac{n\theta}{2} = \cos\frac{3 \times 60^{\circ}}{2} = 0$$