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HARMONIC DISTORTION OF INPUT CURRENT INDUCTION MOTOR ACCORDING TO SWITCHING FREQUENCY IN OFF-GRID PHOTOVOLTAIC SYSTEMS

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Abstract: *The proposed solar system is a combination of solar array, boost DC/DC chopper, DC/AC inverter and three-phase squirrel cage induction motor. This paper is dealing with the design, modeling and simulation of squirrel cage induction motor input current total harmonic distortion depending on switching frequency. The relationship between switching frequency (f_{sw}) and total harmonic distortion for current (THD_I) is examined in this paper. Hereby, an inverse relationship is observed between the f_{sw} and THD_I. PV system is modeled by using Matlab/Simulink and detail study has been carried out for this study in order to evaluate the performance of photovoltaic (PV) off-grid system. The design, modeling and simulation of this topology have been performed from 250 Hz to 51 kHz at switching frequency. Satisfactory performance was achieved for reduction harmonic distortion especially above 1 KHz switching frequency values. Low harmonic distortion has many benefits in power systems such as noiseless operation, less power loss and long life. Therefore, it is presented the Modeling & Simulation of solar inverter feeds three-phase squirrel cage induction motor in Matlab/Simulink software programming. Analytical expression of relationship between THD_I and switching frequency has been obtained by curve fitting method consequently.*

Key words: *Switching frequency, Solar array, Curve fitting method, Total harmonic distortion for current (THD_I), Stand-alone PV system*

1. Introduction

Solar energy is one the most important of the renewable resources that use the abundant and free energy from the sun having clean, inexhaustible and environment friendly cyclic operations. It is a scientific fact that the energy of the rapidly increasing demand against available energy resources a very short time will run out [1]. Off-grid PV Systems are mainly designed to operate independently of the electrical network. PV panel, which converts sunlight to electrical power. The use of photovoltaic systems as clean source of energy from the sun has been quickly increasing. PV energy is most popular owing to its major advantages, such as no fuel and no pollution [2, 3]. This paper is regarding the design, modelling and simulation of input current squirrel cage motor harmonics distortion depending on switching frequency.

The relationship between switching frequency and input current of squirrel cage induction motor THD_I are examined in this article [4-6]. Thus, an inverse relationship is observed between switching frequency and input current of squirrel cage induction motor THD_I. The schematic diagram of the system is as shown in Figure 1.

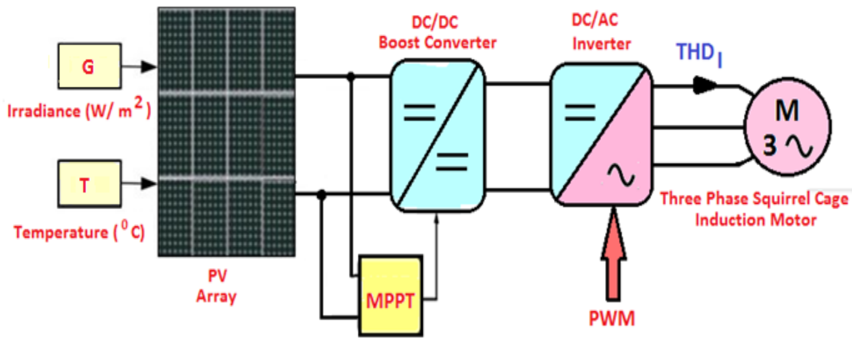

Figure 1. Schematic Representation of Off-Grid System

The cells are designed in modules then modules are interconnected as arrays. The modules might have top out point power depending upon the intended application ranging from few watts, to more than 300 Watts. The ordinary arrays can provide the power by the line-up of 100 Watt-kilowatt, while megawatt arrays do exist. The most important reason for the deterioration of the voltage waveform, the correlation between the terminal voltage and current with non-linear loads are non-sinusoidal sources. Even if nonlinear loads are low powering solar system, they distort sinusoidal current and voltage waveforms. Harmonic components causing serious pollution problem solar system, and they also reduce the quality the energy supplied to the load or consumer. Changing of sun light irradiance also affects the amplitude of the harmonic components. To maximize of output power PV system, repeatedly tracking the maximum power point (MPP) of the system is necessary. The MPP be linked temperature and irradiance of panel and the PV power system simulate by using Matlab/Simulink program [5-7].

2. Harmonics Distortion in Solar Energy System

Harmonic currents generated by non-linear electronic loads, or non-sinusoidal sources. Harmonics increases day by day in solar power system. As a result, harmonic components causing serious pollution problem in solar power system, and they also reduce the quality of energy give to the load. In addition they cause heat losses and resonance problems in solar system. Solar inverters, DC/DC boost converter and battery chargers are the most significant harmonic sources in PV power systems. The input current of the squirrel cage induction motor used in the Simulink circuit is as given in Equation (1).

$$1.341 Sin(17\omega t - 98.11) + 1.495 Sin(19\omega t - 97.7) \quad (1)$$

The stator current of three phase squirrel cage induction motor is as shown in Figure 2.

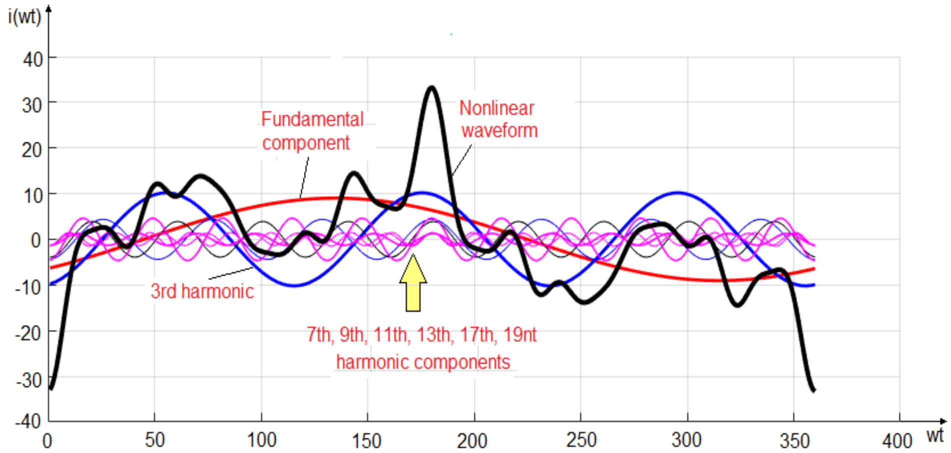

Figure 2. Squirrel cage induction motor stator current and harmonic components (at 250Hz switching frequency)

The converters which used in off-grid PV system are the great harmonic source. Voltage and current harmonics are created by nonlinear loads, and these harmonics cause many problems. The harmonics generated in the PV power converting systems greatly vary with the solar irradiance. The odd harmonics have greater impacts on power quality than even harmonics as they have higher magnitude [8-10]. The current THD is more sensitive on the fluctuation of solar irradiance than the respective voltage THD. Current THD greatly decreases with the increase in the solar irradiance while voltage THD slightly increases with increase in solar irradiance. Power factor varies linearly for values of solar irradiance lower than 200 (W/m^2) and remains close to unity for higher solar irradiance values. In addition, reactive power injection increases at low irradiance. Such as increasing power losses, degrading the conductors, and have negative effect on the distribution systems and other electrical segments [9-11]. Harmonic distortion is generally caused by a nonlinear waveform in PV power systems. Harmonics in the power PV system will cause in the following damage:

- Overheating of solar PV equipment such as solar cables, converters, battery and PV panels
- Incorrect operation of MPPT algorithm.
- Increased internal energy losses in PV power system.
- Causing elements failure owing to high total harmonic distortion.
- Shortened life span of PV device.
- False triggers converters of power electronics.
- Errors measurements voltage, current and power in PV system.
- Increased voltage drop in PV solar system.
- Changes of power factor in the PV system.

THD_I or Total harmonic distortion for current is a common measurement of the level of harmonic distortion present in electrical power networks. The THD_I term expresses as effective value of the all harmonics, divide by the effective value of its fundamental of current. The distortion as a percentage of total harmonic distortion for current is defined as follow:

$$THD_I = \frac{\sqrt{\sum I_n^2}}{I_1} \tag{2}$$

Where In, is the effective current of the nth harmonics, I1 is the effective current of the fundamental frequency. THD_I or Total harmonic distortion for current is a common measurement of the level of harmonic distortion present in electrical power networks. If the harmonics components are equal to the "0", total harmonic distortion will be equal to the "0" where, In, is the effective voltage of nth harmonic and n=1 is voltage of the fundamental frequency. Voltage and current waveform distortion due to harmonics can lead to the solar system and electrical consumer either damaged or out of order. The analytical solutions and Matlab/Simulink applications have been observed that fit harmonic components occur in the solar power system. The presence of harmonic currents and voltages of the power system means that the degradation of sinusoidal waves. Deteriorated waves called non-sinusoidal waves [12, 13].

A lot of the harmonic problem is caused by the 3^{rd} component. Since the 3rd harmonic is the highest amplitude after the the fundamental component. 3rd, 5th , 7th etc. harmonics component are in the PV system. The harmonics current also flows from neutral and neutral gets overheated. All harmonics decrease the quality of a power PV system and loads connected to it. triples harmonics are significant because the harmonics in each conductor are in Phase. Triples harmonics can therefore be much more damaging. The low order time harmonic effects can be minimized since both stator and rotor are supplied from converters. Voltage drops may occur in PV power system due to harmonics [14-16].

3. Stand-Alone PV System Configuration

The purpose of this study to find optimal input current distortion of three-phase squirrel cage induction motor. A DC to DC boost converters is used when the voltage required by the inverter. Three-phase inverter transfer energy to three-phase squirrel cage induction motor. The purpose of this study is to analyses relationship between switching frequency and input current distortion of squirrel cage induction motor.

To compute the total harmonic distortion (THD) generated by PV system feeding a three-phase squirrel cage motor, and examine the change input current motor THD_I depends on the carrying frequency of PWM. Thus, we can analyses the harmonic that will be generated by the PV systems and thus, design the circuit in Matlab/Simulink. Many techniques were proposed to reduce the size of the direct current (DC) link capacitor while maintaining a good inverter power quality so that a more reliable film type capacitor can be used [15-18]. The smallest unit of PV systems is photovoltaic cell. A PV cell is solid-state semiconductor devices which generates electricity when it is exposed to the light so that PV cell can generates around 2, 5 watts at almost 0.48 volt DC and also the cells have to be connected in series and parallel in order to produce high-efficiency in solar energy applications.

The distortion of input current of squirrel cage induction motor can be reduced by changes of switching frequency. The topologic of off-grid PV system is given in Figure 3, which consists of PV array, a boost DC chopper and three phase inverter connects at three-phase squirrel cage induction

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motor. There are two operational modes in the system according to the different working statuses of PV panels, battery and mains supply. The Matlab/Simulink software package can be advantageously used to simulate solar PV system, and analysis of solar inverter. DC link in solar system contains pulsation. Large electrolytic capacitors are connected to the DC link so as to absorb this pulsation so that the DC link voltage ripple can be kept small. The all PV system has been simulated with Matlab/Simulink program. Model off-grid PV system is as shown in Figure 3.

Integrated system has PV array as sources of energy. Therefore, the characteristic of energy storage for a PV system will be explained as well as some specification and standards for a off-grid connected PV system. The simulation of total solar inverter system is given in Fig. 6 Solar cell array and battery is connected with IGBT transistor based three-phase inverter, which further connected to the squirrel cage induction motor. Here ideal switch has been used at DC/DC boost chopper. In practical, there should be a voltage drop across it. As here the ideal switch has been used there is no voltage drop. The purpose of article simulation and analysis of PV based solar single-phase inverter output current distortion depends on switching frequency.

Advantage of PWM Techniques are; while practically no current does not flow when the switch is off, as little as negligible voltage drop on the key switch is turned on. In this way, as well as the lack of power loss, PWM technique very much in line with digital control units. The system changes the on-off switching can provide fit that is so much more comfortable. Also in the embodiment relating to communication techniques and PWM duty cycle of the signals used in communication technology often used. Thus, the desired signals on channels with various adjustments can be obtained. The Simulink model of the solar PV system could be used in the future for extended study with different of a boost DC/DC chopper, DC/AC inverter varied topology [17]. The proposed solar system is a combination of a boost DC/DC chopper, DC/AC solar inverter and three-phase squirrel cage induction motor as shown in Figure 3.

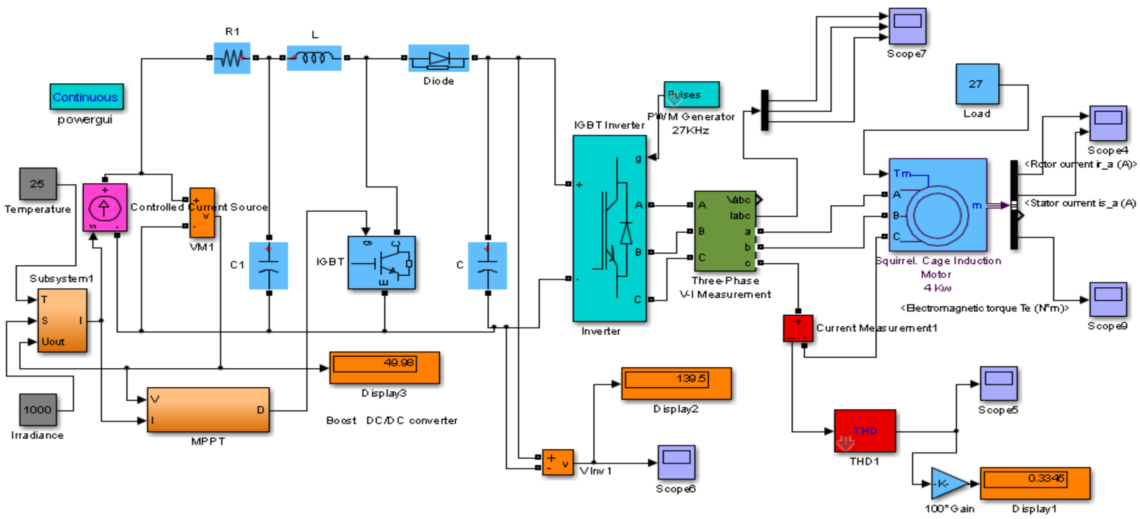

Figure 3. Model Off-grid PV System (27 KHz switching frequency).

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The design, modelling and simulation of this topology are performed by using Matlab/Simulink programming for range of 0.6 kHz to 51 kHz of switching frequency. This shows the satisfactory performance of mitigation harmonic distortion at 27 kHz switching frequency. Thus, we present Modelling & Simulation of solar inverter that feeds three-phase squirrel cage motor in Matlab/Simulink software program. The results of relationship between THDI and switching frequency are obtained in Matlab/Simulink software program [19]. Matlab/Simulation has been done for different values switching frequency.

4. Changing of Output Voltage DC-DC Boost Converter

Therefore, the inductor will oppose change or reduction in current. Thus, the polarity will be reversed. There are many types of DC-DC converters such as buck converter, boost converter, and buck-boost converter. Power inverters are electronic device or circuitry that changes direct current to alternating current. Inverter output voltage waveforms not sinusoidal, therefore, they contain harmonics. Output voltage of square wave is acceptable in low and medium power, whereas, in high power applications ask sinusoidal waveforms. Output voltage of a boost DC-DC converter is as shown in Figure 4.

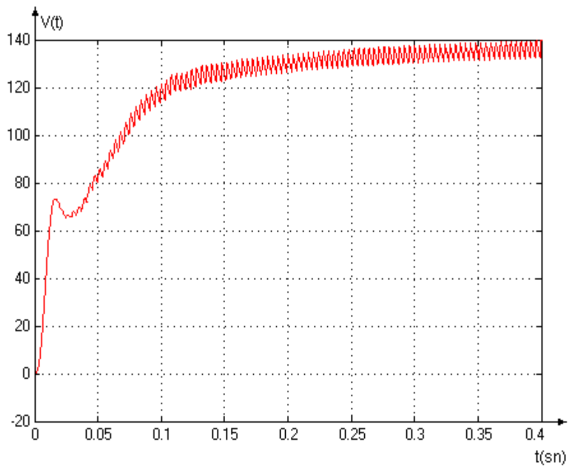

Figure 4. Output voltage of a boost DC-DC converter.

They are connected to the DC bus that could be connected to a different energy storage system, or inject the current directly with a DC/AC inverter. Performance of proposed inverter is verified with exhaustive simulation results on Matlab program. Functions of DC-DC converters have some functions. Capacitor is used to filter ripple currents on DC link. There ripples are caused by power semiconductor IGBT switching. Capacitors are also used to keep the DC voltage stable.

4.1. Electrical characteristics of PV inverter

Inverter which converts the DC waveforms into alternative current (AC) waveforms via a set of solid state switches, here IGBTs are used, that essentially. PV systems use inverters to get connected to

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load that utilize alternative voltage. However, solar inverter is a harmonics source. Universal bridge is implemented as IGBT based inverter with parameters as two arm bridge and four pulses. The results of the different switching frequency depend on total harmonic distortion for İNPUT current of squirrel cage induction motor. IGBT based bridges are used as the inverter operating voltage is low and are connected in parallel with each other. This PV inverter convert direct current to alternating current. IGBT is used as switching element in the inverter. PWM generator block is used to produces triggering pulses to IGBT transistor using in single-phase inverter. These pulses are from 0,6 kHz to 51 kHz. The change of inverter output phase to neutral voltage signal is as shown in Figure 5.

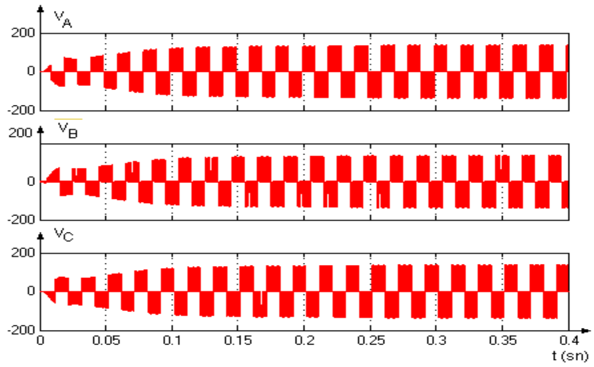

Figure 5. Output voltage of three- phase inverter

The system has been simulated with Matlab/Simulink software program. Solar inverter does not generate excessive noise and harmonics. This study analyzes of input current of squirrel cage motor total harmonic distortion change depending on switching frequency, and also to find the analytic equation between switching frequency (fsw) and THD_I. The simulation is done in Matlab/Simulink software program. Input current of three- phase squirrel cage induction motor is as shown in Figure 6.

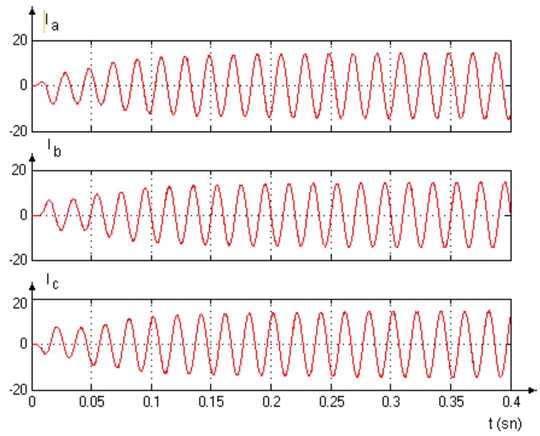

Figure 6. Output current of three- phase inverter.

Solar system structure and working modes are analyzed in detail firstly, then total harmonic distortion belong to switching frequency practical and theoretical analysis based on Matlab/Simulink curve fitting method can be used to summarize the relationships among two or more variables. The

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Simulations is carried out as well for validating between switching frequency and THD_I inversely proportional. The change of three- phase squirrel cage induction motor input current THD is as shown in Figure 7.

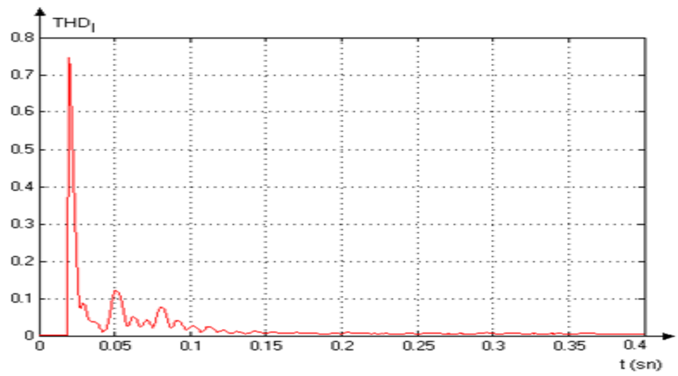

Figure 7. The Change of Squirrel Cage Induction Motor Input Current THD.

The Change of Squirrel Cage Induction Motor Input Current THD becomes stable after 0.4 seconds. No change is observed in THD_I value after 0.4 seconds. Photovoltaic-based inverter outputs current harmonic distortion belongs to switching frequency are primarily discussed in this paper. System structure and working modes are analyzed in detail firstly, and then total harmonic distortion belong to switching frequency practical and theoretical analysis based on Matlab/Simulink. The negative effects of THD_I are such disruption, heating the batteries, overheating the cables, and poor quality of the electrical energy. Total harmonic distortion value was observed that after great value of 1 kHz drop below 5%. At the end of the study, an inverse relationship is observed between the squirrel cage induction motor input current harmonic distortion and the switching frequency.

4.2. Electrical Characteristics of A Three-Phase Squirrel Cage Induction Motor

Induction motors are generally made of two parts, the stator and the rotor. The stator is the standing part of the asynchronous motor. Rotor is the rotating part. The induction motor rotor is of two types, the short rotor (rotor with squirrel cage) and the wound rotor induction motor (rotor with ring). Torque of three- phase squirrel cage induction motor is as shown in Figure 8.

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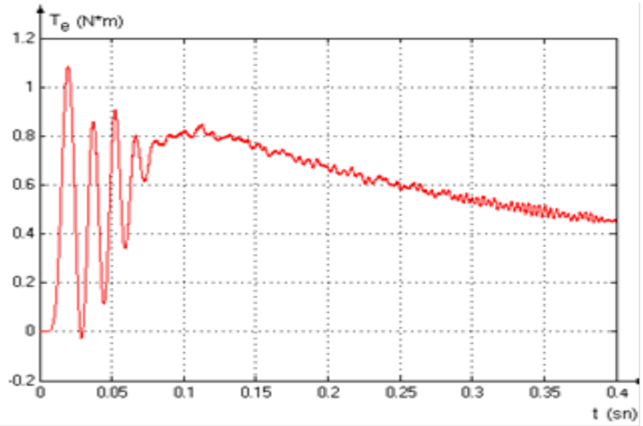

Figure 8. Torque Change Of Three- Phase Squirrel Cage Induction Motor.

The windings, which are placed in the roundabouts in the squirrel cage, are short-circuited with a ring at both ends of the rotor cylinder. In this way, current flows through the shorted rotor conductors to allow rotation of the machine. This engine is also called induction motors with a short-circuit rod. Because induction motors are cheap, do not require too much maintenance and do not make much arc during operation, it is a highly preferred machine.

Even if an asynchronous motor fed from a balanced and pure sinusoidal voltage source, the stator winding distribution due to the internal structure of the machine and therefore the stator ampere-winding distribution is not in sinusoidal form. This cause's structural feature will be released with space harmonics. As a result, currents containing harmonic components will flow through the rotor bars.

Time harmonics will occur if the induction motor is not fed with a voltage in pure sine form. It can be said that the time harmonics are similar effect as space harmonics on the machine. When the harmonic analysis of the source voltage is performed, each component will have effects on the stator and the rotor. Each time the harmonic component will define an equivalent circuit for itself. When the effect of space harmonics is only observed on the rotor, the time harmonics will have an effect on both the stator and the rotor. Rotor and Stator currents of three- phase Squirrel cage induction motor is as shown in Figure 9.

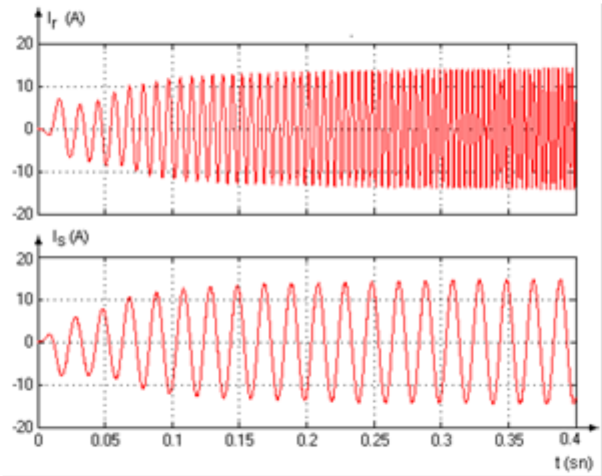

Figure 9. Change of Rotor and Stator Current Squirrel Cage Induction Motor.

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Space harmonics must be originated from machine internal structure and they can never be completely filtered. One of the most studied topics in squirrel cage induction motors are the deep groove effect. This will cause an increase in the motor losses.

5. Analytical Equation Between THD_i and Switching Frequency

The main subject of this study is to find the analytical expression of the relationship between switching frequency and the input current squirrel-cage asynchronous motor THD. Curve fitting method was used to find the analytical expression. For different switching frequency, the THD_I values of squirrel cage asynchronous motor are given below, which based on our study.

X=[600, 1000, 1500, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 5500, 6000, 6500, 7000, 7500, 8000, 8500, 9000, 9500, 10000, 10500, 11000, 11500, 12000, 12500, 13000, 14000, 15000, 16000, 17000,19000, 21000, 23000, 25000, 27000, 29000, 31000, 33000, 35000, 36000, 37000, 38000, 39000, 40000, 41000, 43000, 45000, 47000, 48000, 49000, 50000, 51000]

The following THD values are obtained in different values of the switching frequency.

Y=[4.632, 2.729, 1.826, 1.405, 1.153, 0.9716, 0.8552, 0.8403, 0.6894, 0.6416, 0.8755, 0.5748, 0.7452, 0.6369, 0.7478, 0.5945, 0.7931, 0.5999, 0.5146, 0.4588, 0.6032, 0.4144, 0.8663, 0.4544, 0.7052, 0.7087, 0.6271, 1.006, 0.4503, 0.582, 0.7552, 0.5165, 0.4467, 0.4675, 0.3345, 0.5269, 0.6628, 0.5995, 0.4662, 1.277, 0.4394, 0.4466, 2.142, 0.7389, 0.9094, 0.5350, 0.5962, 0.5508, 0.7552, 1.061, 0.5225, 0.6315]

The distortion rate of the inverter output current is completely dependent on the switching frequency. The variation between the switching frequency and the input current harmonic distortion of squirrel-cage asynchronous motor is shown in Figure 10.

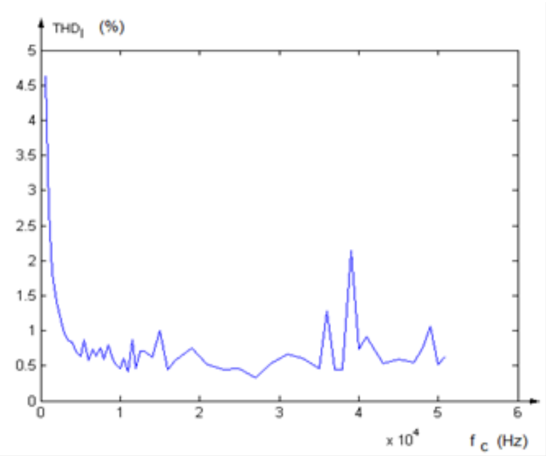

Figure 10. Change of total harmonic distortion depends on switching frequency.

Generally, the data obtained as a result of experimental studies are point values. There is no function definition between the points. So; The "curve fitting" problem is the determination of another

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function closest to the function in point-to-point values of a function, or the search for new functions that can facilitate calculations to replace functions that are difficult to use in practice. It is possible to find the equation of the graph in Figure 10 by curve fitting method. To simplify the operations fsw=x, THD_I=y. Assume that the graphic of Figure 10 occurred by the equation as given below;

$$f(x) = k * x^{-m} \tag{3}$$

Let's take both sides logarithm of equation (3),

$$\log\big(f(x)\big) = \log(k) - mlog(x) \tag{4}$$

The equation (6) can be easily represented as follows:

$$\log\big(f(X)\big) = Y, \quad \log(k) = A, \log(X) = X \tag{5}$$

Equation (5) is converted to the linear equation,

$$Y = A + bX \tag{6}$$

To find k and m values,

$$\gg Polyfit(\log(X) \,.\log(Y)\,, 1) \tag{7}$$

As a result,

ans =-0.2533 2.0729

>> a=exp(2.0729)

a =7.9478

values are found. If we put the values of k and m in the equation (3),

$$y = 7.9478x^{-0.2533} \tag{8}$$

equation is obtained. Then, the equation can be written as below;

x=fsw, y =THD_I is put in the (8) equation

$$THD_I = 7.9478 f_{sw}^{-0.2533} \tag{9}$$

(9) equation is obtained . This new (9) equation was obtained at Matlab program by using the curve fitting method. Changing of equation (9) is as shown in Figure 11.

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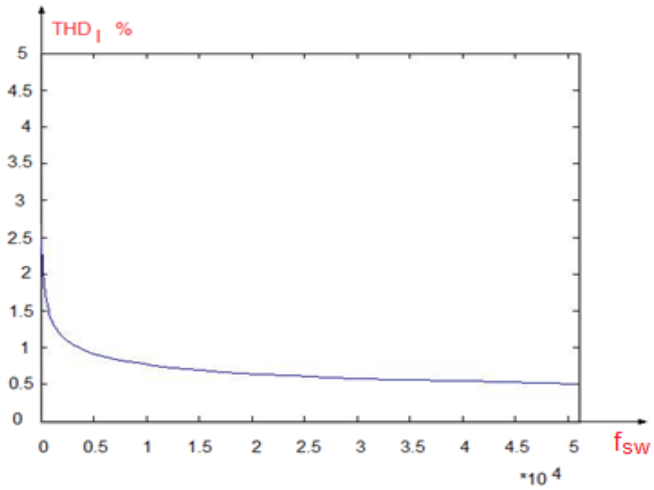

Figure 11. Change of total harmonic distortion depends on switching frequency.

The high THD have negative effects on PV power system such as equipment overheating, motor vibration, neutral overloading and low power factor. As a result of this study, it was observed that there is an inverse proportional change between the switching frequency and the input current of squirrel cage induction motor THD_I.

Table1. Input current distortion of asynchronous motor at different switching frequency values.

fsw (switching frequency	600 (Hz)	1050 (Hz)	9000 (Hz)	27000 (Hz)	40000 (Hz)
THD_I (Total harmonic distortion for current)	1.5733	1.3645	0.7918	0.5995	0.5427

The effect of the switching frequency on inverter output current harmonic distortion is quite high. For less loss and stable operation, harmonic distortion should be kept small for the input current of the squirrel cage induction motor.

6. Conclusion

This study was examined the relationship between switching frequency (f_{sw}) and total harmonic distortion for current (THD_I) by means of using the design, modeling and simulation of squirrel cage induction motor input current total harmonic distortion depending on switching frequency. Harmonic distortion value for the asynchronous motor decreases at high values of PWM's carrying frequency. THD_I of squirrel cage asynchronous motor decreases below 1% when switching frequency is greater than 3 kHZ (f_{sw} > 3 kHZ). Inverse proportional relationship has been observed between f_{sw} and THD_I. The most serious and negative effect of harmonics in rotating machines is overheating especially in rotor and stator circuits. Harmonics cause copper and iron losses in induction machines. The high frequency of harmonic components destroys the rotating magnetic field and causes the machine to work with noise and vibration. In three-phase squirrel cage induction motors, the coil pitch can be shortened to certain values in order to eliminate space harmonics. Analytical expression (Eq.9) was obtained between f_{sw} &

THD_I of the squirrel cage asynchronous motor by using the Matlab software program with the feature of curve fitting method. Satisfactory performance was achieved for reduction harmonic distortion especially above 1 KHz switching frequency values. Hence, harmonic distortions of squirrel cage induction motor values were observed below 5%.

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