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Modelling and Simulation of a Stand-Alone Solar System with A Capacity of 380V, 39A Based on Ferrite Transformers and Half Cut Cell PV Modules

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Abstract

The easy installation of the solar energy system, no need for fuel, low maintenance and operation requirements, makes it the preferred choice to solve the problem of power outage especially in the day of the summer season. The downside of the solar energy systems is decreasing the generated energy with the rising in temperatures, perfect and simple design of the solar energy system makes it durable over a wide range of temperature increases. This research presents the design of 3-ph (380V, 39A) stand –alone solar system at a latitude 32.5 with a high-quality voltage and current even when the temperature reaches to maximum levels. The power system of the project contains: 60 PV modules of a half-cut cell to reduce the losses in connection lines, and two Mn-Zn toroid core ferrite transformers to transition the solar energy to the inverter with appropriate voltage efficiently. Control system is implemented based on PI controllers for switching function at a certain values of a modulation index parameter (m). The system is modeled and simulated in MATLAB/Simulink, simulation results demonstrate that the rated voltage and current have been obtained with minimum values of Total Harmonics Distortion (THD) and modulation index parameter less than 1.

1. Introduction

In recent years, the demand for electric power has increased due to population expansion and economic development. Most feeders in Iraq suffer from overloading in summer season due to conditioning loads and increasing the resistor (Ω) of transmission lines. Exploiting renewable energies in installing stand-alone electrical power projects can help in mitigating the distribution systems loads. As well as investment in renewable energies has many other critical benefits; diversity of energy sources, which plays a vital role in providing the reliable and continuous electrical energy, reducing the dependence on fossil fuels, providing job opportunities, mitigating the climate changes. Solar energy is plentiful in Iraq, where the average solar radiation in the summer is between (800W/m2 - 900W/m2) [1]. Photovoltaic (PV) modules installing can help in providing continuous electricity during hot days where the electrical current cut off are more. A stand-alone photovoltaic solar system is introduced in this research; the system is installed in Kut city located on a latitude 32.5° to power houses with a line current 39 A. The system includes; half cut cell PV modules, step up ferrite transformer, inverters, and harmonics filters. The absence of expensive and numerous batteries makes the system smaller in size, lower maintenance requirements, and cost-effective. Several techniques have been used to implement stand-alone solar systems; 3-phase inverter to convert DC voltage into AC voltage and using 3-ph iron transformer to step up the voltage to the rated value. The use of iron transformer makes the system expensive and heavily in addition to iron and copper losses of the iron transformer. DC-DC boost converter to boost the DC voltage and convert it into AC voltage by a 3-ph inverter. DC-DC boost converter have a limited boost factor, so multi stages must be used to raise the DC voltage to a required level. And the efficiency of the boost converter no more than 80%. 3-ph Z-source inverter raises the voltage produced from solar PV modules and converts it into AC voltage, Z source inverter has drawbacks, such as; the limited boost capability, intermittent input current, needs a big size of inductors and capacitors, and low efficiency about 65% [2]. The main objectives of this research are to mitigate the impact of temperatures rising on the productivity of the solar energy system and reduce losses in the system which caused by high currents. High frequency transformer based inverter system has been used, as it have many features over the mentioned topologies: high efficiency greater than 90%, small area of hysteresis losses [$Hysteresis\, losses \propto (K/f)$][3], very high resistance, so no need to lamination to reduce the losses of the eddy current, less copper and electrical losses due to few turns number [$Turn/volt = 1000\ /(2.05 \times f \times A)$][4]. Half cut cell PV modules have been used to minimize the losses in connection lines (L) as dividing the cells and the modules lead to divide the connection lines and reduce the resistor $(R \propto L/A)$, as well as currents will be divided, since the current relying on the cell area about (24 – 35) mA/cm2 [4], dividing the current leads to reducing losses in the solar PV module[5]. Fast response closed loop voltage with PI controllers to stabilize the output voltage and current at set points has been proposed. The quality of the inverter is indicated by the modulation index parameter, which should be greater than (0) and not exceeds (1). When modulation index greater than 1, distortion results in output waveforms [6]. Simulation results demonstrate the rated output 380v, 39A, 50Hz is obtained after a short time of transient with modulation index parameter less than 1 and minimum values of the Total Harmonics Distortion (THD) over a wide range of temperatures rise.

2. Influencing Factors on PV Modules Productivity

The factors that most influence on efficiency and performance of PV modules are; intensity of the solar radiation, the increase in temperatures, tilt angle of the solar modules, the shadow, and the dust. High temperatures is the most influential factor on the productivity of the PV modules in Iraq, where temperatures reach more than 50°C in July and August months. In contribution [7] the temperature of the solar module has been calculated from the following equation:

$$T_{CELL} = T_{AIR} + \frac{NMOT - 20}{80} \times S \tag{1}$$

TCELL is the temperature of the solar panel
TAIR is the ambient temperature
NMOT the PV module temperature under conditions (ambient temperature 20°C, solar radiation intensity 800 W/ m2, and speed of air 1 m / sec)
S is the correlation between the ambient temperature and the panel temperature, it is the solar radiation in mW/cm2

The characteristics of the half cut cell PV modules which are using in this project at standard conditions (temperature of the PV module 25°C, and the solar radiation intensity 1000W/m2) are:

Maximum power point voltage (VMP) = 40.9v, maximum power point current (IMP) = 10.2A, maximum power (PM) = 417.18W, nominal maximum operating temperature (NMOT) = 43 ± 3, and temperature coefficient (TC) = -0.35%.
The NMOT value is 40 at the winter season and 46 at the summer season.
When TCELL is 50°C, and the solar radiation is 982W/m2, TCELL becomes 81.92°C according to the equation 1.
The generated voltage from the PV module is reducing by 0.35% for rising in PV module temperature1°C above 25°C.

$$\Delta T = T_{CELL} - 25°\mathrm{C} \tag{2}$$

ΔT is the increase in temperature of the solar panel above 25°C, substitute TCELL = 81.92°C in equation 2 result:

$\Delta T = 81.92°C - 25°C$
$= 56.92°C$

$$V_{CR\%} = \Delta T \times T_C \quad (3)$$

VCR is the decrease in generated voltage, Tc is the temperature coefficient of the solar panel, substitute ΔT = 56.92°C, and Tc = 0.35% result:

$V_{CR}\% = 56.92°C \times 0.35\%$
$= 19.9\%$

$$G_R\% = 100\% - V_{CR}\% \quad (4)$$

GR the generation ratio, substitute VCR% = 19.9% result:

$G_R\% = 100\% - 19.9\%$
$= 80\%$

$$V_G = V_{MP} \times G_R \quad (5)$$

VG is the generated voltage, substitute VMP of the panel = 40.9V, and GR = 0.8 result:

$V_G = 40.9V \times 0.8$
$= 32.72V$

$$P_G = V_G \times I_{MP} \quad (6)$$

PG is the generated power, substitute VG = 32.8V, and IMP = 10.2A result:
$P_G = 32.72V \times 10.2A$
$= 333.744W$

So, power and voltage produced by PV module will decrease from 417.18W, 40.9V in standard conditions to 333.744W, 32.72V in conditions (TAIR 50°C, solar radiation intensity 982W/m2, and TCELL 81.92°C).

3. Ferrite Transformer

Ferrite is a combination of iron oxide with oxides or carbonates of one or more metals such as a zinc, manganese, nickel or magnesium. Manganese-zinc ferrite core transformer is suitable in applications with operating frequency range from 20kHz to 3MHz, it has mainly the following features [8]: higher permeability, higher saturation, lower resistivity that it can conduct low electric power and the electric field intensity is higher, soft ferrite core so change in magnetic direction with slight hysteresis losses. For a high power, a push-pull inverter is effective with ferrite transformer because it makes bidirectional use of a core providing an output with low noise and ripple [9]. Ferrite transformer is driven by a square wave with 50% duty cycle that the losses is (0 – 15) % smaller than in the case of sine wave [10]. Toroid core shape is preferred, as it has many advantages [11]: lightweight 50% lighter than other cores, occupy at least 64% lesser volume in transformers as they are smaller than other cores, has a higher magnetic field as most of the magnetic field is saved within their closed-loop structure, wound in an enclosed magnetic field result in short windings and therefore lower impedance which results in higher efficiency and higher electrical performance, dissipate heat well that it allows natural air convection around it's windings. The core of the ferrite transformer can be selected by WaAc product [12], where:
Wa is the window area
Ac is the effective core cross sectional area.

The relationship between WaAc and output power is obtained by starting with Faraday's Law. For the square wave [13]:

$$E = 4 \times B \times \mathrm{Ac} \times N \times f \times 10\text{^}{-8} \quad (7)$$

E is the electrical field, B is the magnetic flux density, N is the turns number, f is the electrical field frequency

$$NAc = \frac{E \times 10^{\wedge}8}{4 \times B \times f} \tag{8}$$

Winding factor (K):

$$K = \frac{N \times Aw}{Wa} \tag{9}$$

$$K = \frac{N \times Aw}{Wa} \tag{10}$$

Aw is the wire area in cm2, Wa is the window area in cm2
Combining the equations (8) and (10) result:

$$NAc = \frac{K \times Wa \times Ac}{Aw} \tag{11}$$

K = 0.2 for toroid cores
Solving for WaAc result:

$$WaAc = \frac{E \times Aw \times 10^{\wedge}8}{4 \times B \times f \times K} \tag{12}$$

WaAc in cm4

$C = \frac{Aw}{I}$ or $Aw = C \times I$, $e = \frac{Po}{Pi}$, $Pi = E \times I$

C = 4.05 x 10-3 cm2/A for square wave and toroid cores
Efficiency (e) = 90% for toroid transformer
Thus:

$$E \times Aw = \frac{Po \times C}{e} \tag{13}$$

Substituting 13 in 12 result:

$$WaAc = \frac{K' \times Po \times 10^{\wedge}8}{B \times f} \tag{14}$$

Where;

$$K' = \frac{C}{4 \times e \times K} \tag{15}$$

For square wave operation $K' = 0.00633$

Reduction in flux density (B) lower than 2000 kg with high frequency greater than 30kHz is necessary to maintain the losses in the core in mW/cm3 [14]. High frequency 58kHz has been used to minimize the core volume and to match with available standard cores. When the frequency greater than 35kHz the core is saturated at flux density less than 2000G. As shown in Fig. 1 for 58kHz, B is equal to 1500G.

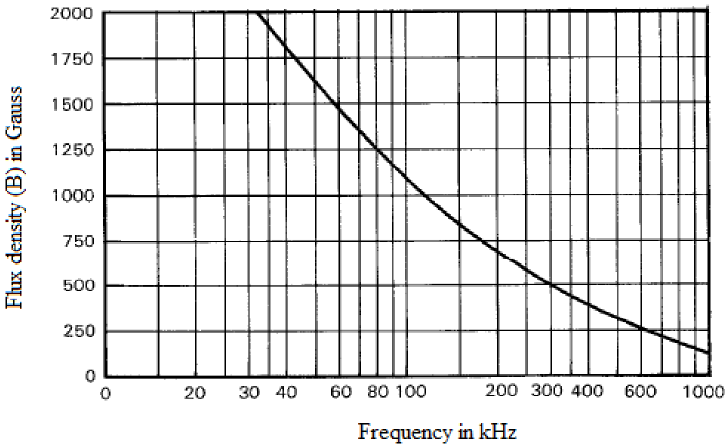

Fig. 1 *The relationship between the frequency and the flux density*

With a capacity of 24.9081kW, f = 58kHz, and B = 1500G, WaAc for the toroid ferrite core is calculating as following:

$$WaAc = \frac{0.00633 \times 24908.1 \times 10^{\wedge}8}{58000 \times 1500}$$

= 182cm4

To reduce space capacity of the inverter and reduce electrical losses, two transformers with WaAc = 91.2 cm2 have been used instead of one transformer with WaAc = 182cm4

The parameters of the core are demonstrated in Table 1. The WaAc product is meet with the system design requirements

Table 1 *The parameters of the toroid core*

The Parameters	The Values
Ordering code	0_48626TC
Outer diameter (OD)	0_48626TC
Inlet diameter (ID)	55.5 cm
Height (HT)	25.4 cm
Window area (Wa)	24.2 cm2
Core area (Ac)	3.76cm2
WaAc product	91.2 cm4

Fig 2 depicted the two dimentional figure of the toroid core. Inlet diameter is 55.5cm, outer diameter is 85.7cm, and the thickness of the toroid core is 25.7cm

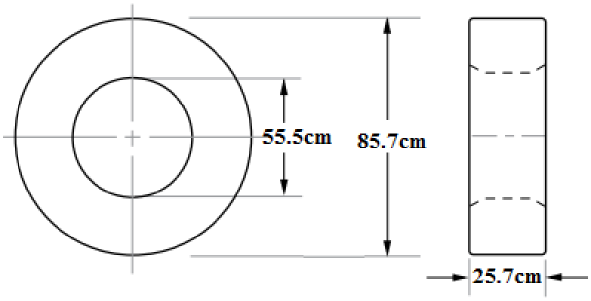

Fig. 2 *The two dimensional figure of the toroid core*

The primary and secondary turns are determined from equations 16 and 17 as following [15]:

$$Np = \frac{\text{Vp} \times 10^{\wedge}8}{4 \times B \times Ac \times f} \tag{16}$$

Substitute Vp = 613.5, B = 1500, Ac = 3.76, f= 58000 result:

$$Np = \frac{613.5 \times 10^{\wedge}8}{4 \times 1500 \times 3.76 \times 58000}$$ =46.8 turn =47 turn

$$Ns = \frac{\text{Vs}}{Vp} \times 47 \tag{17}$$

Substitute Vs = 800 result:

$$Ns = \frac{800}{613.5} \times 47$$ = 61.2 turn = 63 turn

4. The Power, and The Control Systems for The Project

Connection techniques of the PV solar systems are depending on the size of the system, location where the system has been installed, and the purpose of establishing this system. There are four techniques to connect the PV solar systems to the national grid and consumers; off-grid solar system, on-grid solar system, hybrid solar system, and stand-alone solar system. Off-grid solar system charges the batteries from the national grid when the generated power from the PV solar modules is insufficient to charge the batteries, off-grid solar system is used to operate loads during the power outages. An on-grid solar system strengthens the national grid by supplying it with electrical current during the day. Hybrid solar system feeds the national grid with the electrical current that is surplus to the load's need. Stand-alone solar system is an independent on the national grid, it can be a solution for providing electricity in locations where the national grid electricity is not available, such as remote areas. It can also be used to reduce the electricity bill by shedding loads from the national grid and powering it via off-grid solar system during the day. The stand-alone solar system in this research consists of PV solar modules as DC current source and an inverter to convert the DC current into AC current for powering the loads. The D.C electrical power source includes four strings of PV modules each string consists of 15 PV modules. The total voltage is 613.5v (40.9×15) and the total current is 40.8A (10.2×15). Full bridge inverter is inverting the voltage and current at a high frequency (58 kHz), that are feeding ferrite transformer primary windings. Ferrite transformer has been modeled in MATLAB/Simulink with a high core resistor and a low core inductance (Rm = 20Ω, Xm = 0.8H). The square AC voltage and current are converted into filtered DC voltage and current using a bridge rectifier and a 1-ph filter. 3-ph inverter converting the DC voltage and current into 3-ph sinusoidal voltage and current. At the output of the 3-ph inverter a 3-ph filter is connected to filter out harmonics with frequencies (Fh) equal to multiples of switching frequency (Fs) as presented in equation 18 [16]

$$Fh = (n \times Fs) \mp (K \times 50\,Hz) \tag{18}$$

The (Vr.m.s) value generated from the inverter is given by the equation 19 [17]:

$$(Vr.m.s)value = (Vd.c)value \times 0.612 \times m \tag{19}$$

m is the modulation index

At standard conditions the inverter input voltage must be 800V to get (380V, 39A) with the modulation index parameter equal to 0.776. And the modulation index parameter must increase to less than 1 to compensate the reduction in generated voltage. The relationship between the input DC power and the output AC power for an electrical system is depending on the energy balance law [18]:

$$VdcIdc = VaIa + VbIb + VcIc \tag{20}$$
$$VdcIdc = \sqrt{3} \times VL \times IL \tag{21}$$

The block diagram of the voltage and current in this PV solar system is demonstrated in Fig 3.

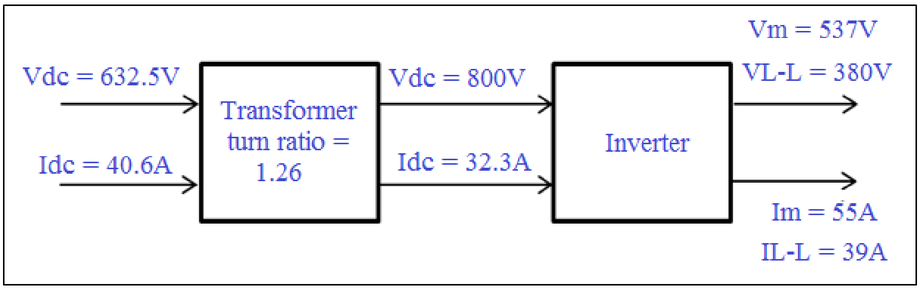

Fig. 3 *The block diagram of the voltage and current in the PV solar system*

Control system includes voltage regulator, and sinusoidal pulse width modulation (SPWM) generator. Voltage regulator includes Park transformation (abc_to_dq0) and reverse Park transformation (dq0_to_abc). The voltage control loop based on a proportional-integral (PI) controllers regulates the load voltage to 380V, 50Hz. PI controller has fast time response compared with non-linear controllers, which are having limited performance of response time and damping profile. The difference between (Vd , Vq) references and (Vd, Vq) feedbacks is the input of the PI controllers. A good performance is obtained by a well tuning for the PI controllers, an emperical tuning is a common stratgy and used in this project.

The transfere function of the PI controller is given by the equation 22.

$$H_{PI} = K_P + \frac{K_I}{S} \tag{22}$$

KP is the proportional gain
KI isthe integral gain
In this control system KP =0.5, and KI =510.

Hypot function for the first PI controller output (Vd) and second PI controller output (Vq) is used to obtain the modulation index parameter [19] as demonstrated in equation 23:

$$m = \sqrt{(Vd)^2 + (Vq)^2} \tag{23}$$

The reverse Park transformation (dq0_to_abc) produces a voltage control signal, which is shown in Fig 4, that each phase generates pulses to trigger two switches in the same arm

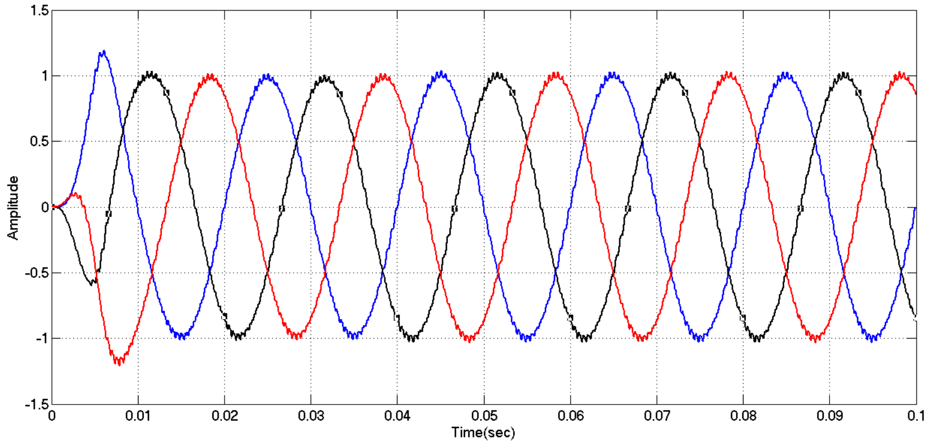

Fig. 4 *Control voltage signal generated by the voltage regulator*

The voltage stabilizer control system is demonstrated in Fig 5

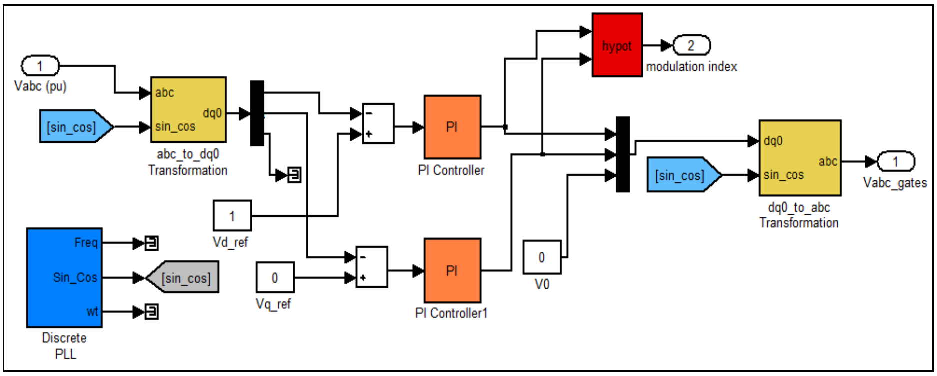

Fig. 5 *The voltage stabilizer of the control system*

The input of the voltage stabilizer is a one phase of the output voltage in p.u, and the output is the modulated signal and the modulation index value. The Phase Locked Loop (PLL) produces sin and cos signals at 50Hz used by Park transformation (abc-dq0) and reverse Park transformation (dq0-abc). The complete system is demonstrated in Fig 6. The values of the 1-ph filter are: L = 200uH, C = 6000uF, and the values of the 3-ph filter are: L = 2mH, C = 3KVAR.

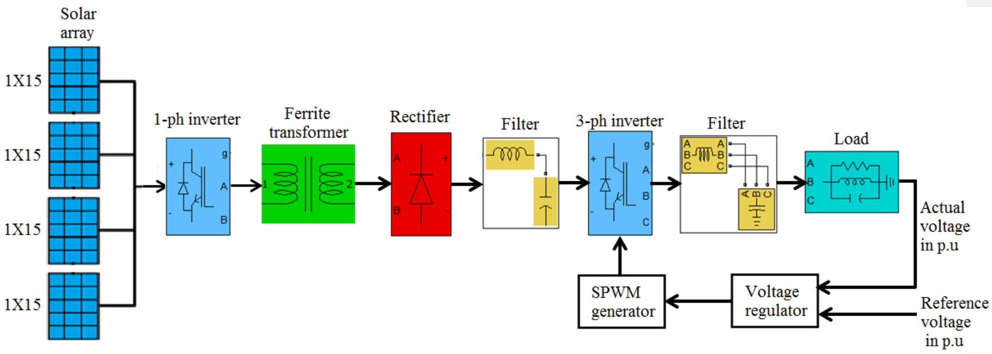

Fig. 6 *The stand-alone PV solar energy system*

5. Modeling Results and Discussion

The proposed system of this project is demonstrated in Fig 7. The 1-ph inverter is controlled by an open loop controller and the 3-ph inverter is controlled by a feedback controller. The sampling time (Ts = 5us) and the run period is 0.1s

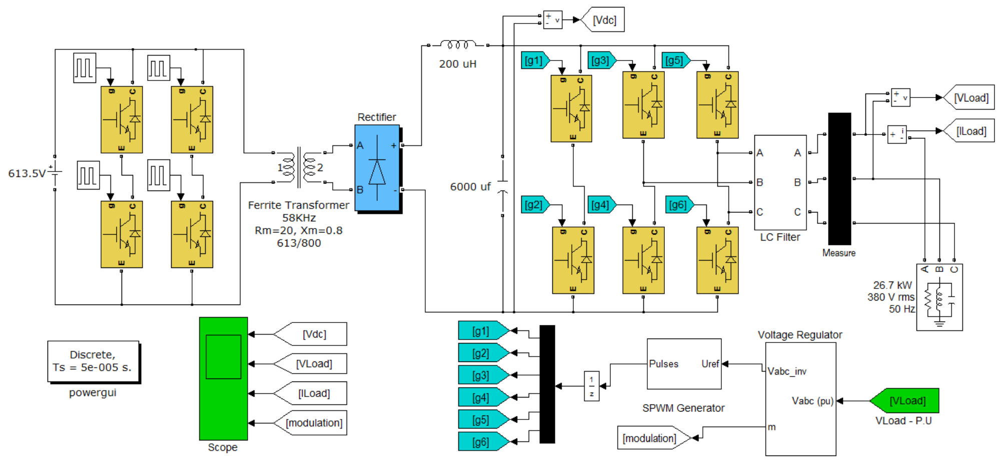

Fig. 7 *Modeling and simulation of the PV solar energy system*

Fig 8 depicts the waveforms of the 3-ph inverter input (DC link voltage), load voltage (Vab Load), load current (Iab Load), and modulation index parameter under the standard conditions, where the generated voltage from the PV modules array is 613.5V

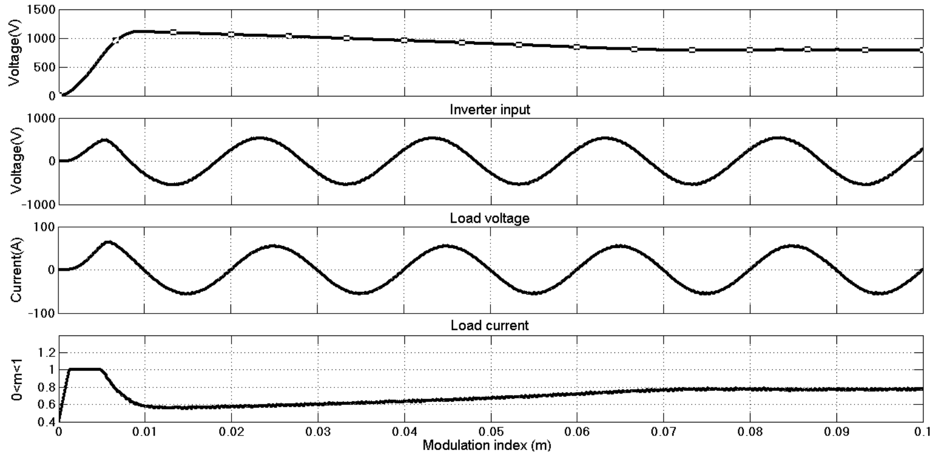

Fig. 8 *The generated waveforms in the standard conditions*

Table 2 presents the increase in modulation index parameter with decrease the generated voltage and power from the PV solar modules. The relationship between the (THD) and the modulation index parameter is nonlinear. THD levels indicate a good quality of the output load voltage. The measurements have been taken through the months (April, June, July, August), where the solar radiation intensity is between (800W/m^2 – 900W/m^2) and the ambient temperature is between (40°C – 65°C) under the sun

Table 2 *The performance of the PV solar project with rising in temperatures*

Ambient temperature (°C)	PV module temperature (°C)	PV module voltage (V)	String voltage (V)	Solar array power (w)	Load Voltage VL(V)	Load Current IL(A)	Modulation index (m)	THD% 0f the load voltage
41	71.87	34.17	512.6	20815.6	380	39	0.81	0.56
44	76.88	33.46	502.5	20383.2	380	39	0.83	0.7
49	81.89	32.75	491.4	19948.4	380	39	0.85	0.85
54	86.87	32.05	480.7	19512.3	380	39	0.88	1
59	91.86	31.32	469.8	19076.9	380	39	0.90	0.98
64	96.88	30.5	460	18635.5	380	39	0.93	0.97

Fig 9 and Fig 10 demonstrate the waveforms at temperatures 49°C, 54°C, and Fig 12 shows the waveforms when the ambient temperature reaches 64°C under the sun

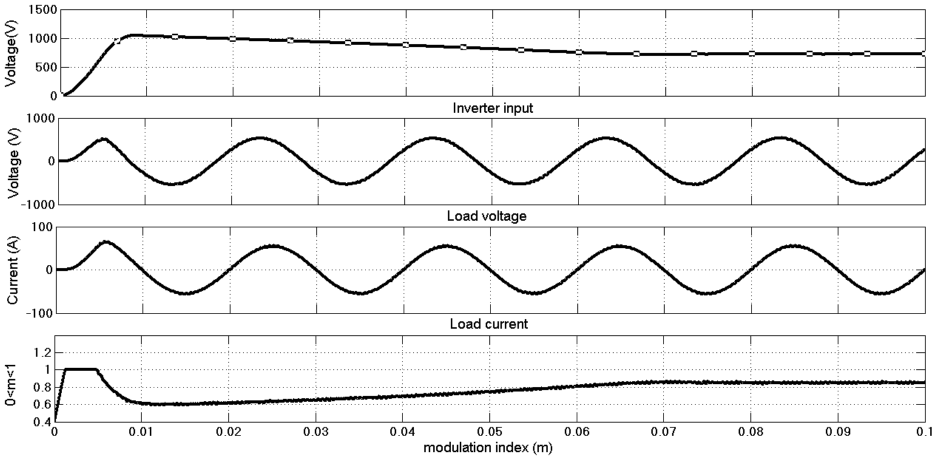

Fig. 9 *The generated waveforms at 49°C. The modulation index parameter increases to 0.85*

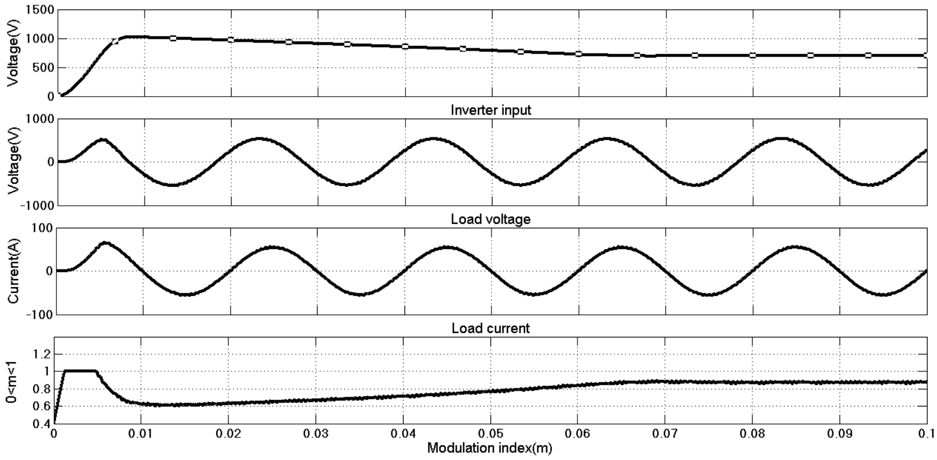

Fig. 10 *The generated waveforms at 54°C. The modulation index increases to 0.88*

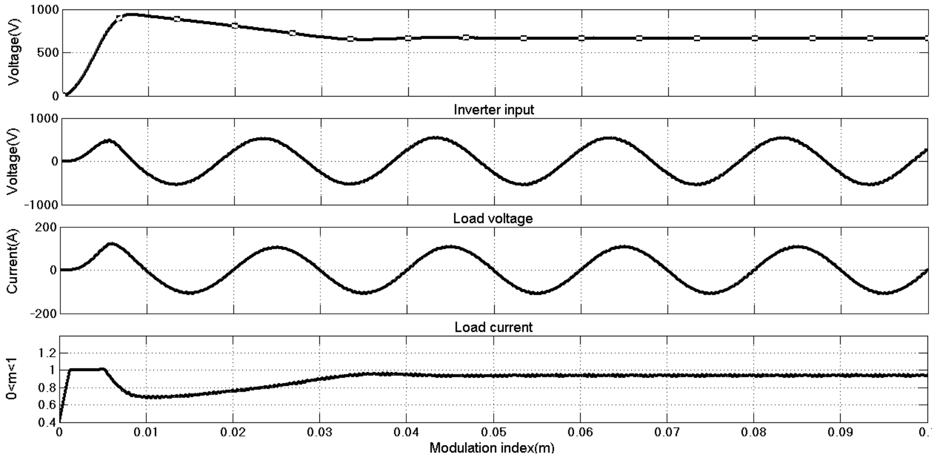

Fig. 11 *The generated waveforms at 64°C. The modulation index parameter increases to 0.93*

6. Conclusions

Despite the drawbacks associated with PV solar energy systems, such as the need for large areas to install solar panels, infrastructure high cost, and decreasing the production of electrical energy with the rise in temperatures, some customers prefer them over diesel generators because of the fuel cost and maintenance requirements. This paper has been presented a stand-alone solar energy system with the perfect design of the control system which is characterized by a fast response in changing the modulation index to match the change in generating voltage. The system gives constant voltage and current of 380v and 39A with the temperatures reaching to the maximum levels. Half cut cell PV modules and toroid core transformers have been used to mitigate the effect of temperatures rising and reducing losses in the system. Simulation results of the DC link, load voltage, load current, and the modulation index parameter have been proved the reliability of the PV solar project in producing the required voltage and current with adequate quality levels under different thermal conditions.

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Conflict of Interest

Commented [MABZ1]: Use Acknowledgement Style

Authors declare that there is no conflict of interests regarding the publication of the paper.

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