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Analysis of 7.5kW Inductive Load Effects on Renewable Energy Source

Odion Joshua[1], Ekom Enefiok Okpo[2] and Promise Joseph Etim[3]
[1]TotalEnergies Nigeria Limited
[2,3]Akwa Ibom State University, Ikot Akpaden, Nigeria
Corresponding Author: Ekom Enefiok Okpo

ABSTRACT : *The increase in reliance on new sources and geometric rate of energy demand due to general acceptance and use of inductive loads in domestic, commercial and industrial sectors necessitate the integration of PV system to supplement the unreliable power supply from the main grid. This research is to examine the workability of inductive loads when supplied from Solar PV soource. Effects of inductive load on PV system were carefully evaluated by deploying an asynchronous motors rated at 7.5kW (10HP, powered from two different power sources. This load was first used on conventional source and secondly, PV system with same power rated capacity of 20.5kW, in order to properly investigate the impacts and effects of inductive loads on PV systems by means of comparison with the conventional counterpart. The major parameters and characteristics under investigation were, the rotor current, speed and electromagnetic torque of the motor on the two power sources. This study deployed two different electric power sources (Conventional source and PV system), which were modelled in MATLAB/Simulink. The result showed a significant reduction in harmonics, improvement in efficiency and stability of the asynchronous machine output when powered with the three-phase conventional electric power source compared to its performance when served from PV system. Higher capacity of Solar PV System is needed to inductive as inertia and transient effects are serious challenges to the system.*

KEYWORDS: *Asynchronous machine, Photovoltaic system, Conventional power source, Electromagnetic torque, modeling, simulation.*

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I. INTRODUCTION

The exhaustion of fossil fuels and the growing energy demand have prompted the exploration of novel and supplementary electric energy resources. Non-traditional energy sources have demonstrated their significance in this pursuit. Furthermore, some of these sources serve as the solve viable option for meeting power needs in situations where conventional power generation is unfeasible or cost-prohibitive to transmit from the source to the destination. In such scenarios, it is imperative that the implementation of power generation using non-conventional sources is optimized to its fullest potential [1]. Solar PV system energy gives a promising solution due to its additional features over other non-conventional power sources; it is relatively abundant in nature and offers a negligible operational cost including transportation or transmission cost. The energy from the sun can be converted into useful electrical energy using photovoltaic technology. Thermal pollution from conventional power plants has a tremendous negative effect on the atmosphere and the environment at large therefore, seamless ways to mitigate its effect is imperative [2]. Inductive loads are critical component of power system that find wide applications in both process industries, homes, institutions and other sectors, due to its high demand in terms of low cost and maintenance, they present notable challenges in power distribution network.

However, due to erratic power supply from the main grid, without intervention from non-conventional sources of power supply such as solar PV system, the energy need from conventional sources could rise dramatically which could otherwise lead to incessant grid failures resulting to great damages to the entire power system components [3]. Asynchronous motors accounts for approximately 45% of the world-wide electricity consumption, resulting in around 6040 million tons of emissions. Studies such as [4] concludes that unless substantial alternative sources are introduced by 2030, energy usage attributed to electric motors and their drive system could surge to 13360TWh annually, accompanied by 8570 million tons of emission each year [4].

Integration of solar based DERs with the main grid results to a hybrid system which is quite complex, however the numerous accompanied benefits from this paradigm have informed the decision of several researchers in this direction. Numerous researchers have dedicated the past decade to the investigating of the performance of renewable energy systems, aiming to mitigate greenhouse gas emissions and achieve more cost-effective energy solution compared to conventional sources, particularly solar power, are playing an increasing pivotal rule in modern power systems. Solar power derives its energy from solar photovoltaic (PV) arrays and electric inverters. These PV arrays are constructed by configuring PV solar modules in series or parallel combinations. PV system have proven to be highly cost effective, especially in remote locations where they provide power for telecommunications, lighting, signage, homes, and recreational vehicles [5]

Micro grids are typically smaller scale power system that rely on local energy resources, such as solar, wind turbines or small-scale generators. While the decentralization can enhance the security of supply, it also means that the micro grid maybe more susceptible to disruptions for instance extreme weather event that affects the insolation level thereby reducing the optimal performance of the System. It is also limited in capacity when compared with the larger centralized grids. This limited capacity can lead to challenges when trying to meet increased energy demands or support rapid growth in the connected loads. The limited connections of IBRs with the main grid also makes it fragile and reliance on local resources.

The influence of Inverter Based Resources (IBRs) on Microgrid Protection was carried out in [6, 7, 8] They studied various challenges faced by IBRs, which include limited fault current, absence of negative sequence current which plays a major role in smart fault detection, the influence of battery state of charge, inverter response time, load inrush current and frequency tracking. Solutions to some of the outlined challenges were proposed. They stated that thermal limit in inverter firmware could be controlled using real time measurement of aluminium heat sinks and cooling water jackets. Since hardware associated with heat removal is expensive, the thermal limit is often the driving factor in overall inverter construction costs.

The literature further reviewed that frequency tracking in grid following inverters have a history of causing instability and revenue lost to the power system. When grid following inverters fail to track the power system frequency, a phase shift occurs and suggested that all inverters should be moved to grid forming inverters with limited or no frequency tracking dependence. If a micro grid is reliant on photovoltaic system, on a cloudy day, high load can result to outage.

To prevent this interruption, they proposed that off grid renewable micro grid should be designed such that PV generation nominal power is sized six to eight times the average load renewable target and battery discharge capability sized from three to four times the peak load. They concluded by stating that carrying out automatic load shedding (tripping off) non critical loads with the aid of programmable protective relays (PPRs) can also be a low-cost solution. However, the overall cost of implementing such technology is extremely high.

Review of Related Work

The research on Modelling and Performance Analysis of a Solar PV Power System Connected to a Three Phase Load Under Irradiation and load Variations was carried out in [9], showed that maximum power point can be tracked using photovoltaic simulation system particularly MATLAB/Simulink simulation tool. The study also deployed advanced control algorithm to regulate a DC-DC boost converter for precise generation of maximum power point of the photovoltaic generator that facilitate it seamless integration with the Pulse Width Modulation (three phase inverter).

The study on photovoltaic partial shading performance evaluation with a DSTATCOM controller was carried out in [10, 11], deployed a novel approach that addresses issues like DC offset rejection and assessment of its performance compared to conventional protection resonant (PR) controller and adaptive protection resonant controllers, the study demonstrated the real time performance improvement of a solar photovoltaic D-STATCOM system connected to the grid under partial load shading conditions, it deployed inverter protection resonant(IPR)-based second-order generalized integrator (SOGI) controller to enhance power quality, reduce DC offset, and increase system stability which was confirmed through analytical and experimental validation.

Studies conducted in [12], discussed on the performance of DC micro grid system using photovoltaic module, incorporating boost converter with maximum power point tracker (MPPT) to enhance efficient power extraction. It was observed that ripples in resistive load are less compared to inductive load, the study deployed PSIM software to validate the modelled system.

The research carried out in [13, 14] developed and tasted an induction cooker (IC) when it is been served from the off-grid photovoltaic source, a significant energy and exergy efficiencies of 11.8% and 17% respectively was realized. Additionally, the research demonstrated the advantage of using steel pots with specific dimensions for optimal energy transfer, and concluded that penetration of the micro grid will reduce potential environmental impact of greenhouse gases and cooking cost in remote areas. The study in [15] present a comprehensive study on the speed control of inductive motor using MATLAB version 2011b it deploys the analysis of motor parameters and employs photovoltaic (PV) array as source the study concludes that deploying PV to serve induction machine will facilitate significant cost saving due to the numerous uses of ac machines in most industries.

There was a similar research work carried out in [16], but the focus was on comparing the performances of 15kW on both solar PV and conventional sources. Higher capacity of PV source was recommended for optimal performance to be achieved. [17, 18] worked on solar PV system, but the two papers did not focus on comparing 7.5kW loads. The advent of Solar PV system as electricity source has brought relieve to power consumers. The conventional sources had remained complex in management and unreliable in supply due to it complex interconnectivity nature irregular and poor-quality supply. The PV system efficiency on resistive loads had attained appreciable level of efficiency, while inductive load aspect remains a great challenge. Numerous researchers have explored this aspect however, the assessment of inductive load performance when powered by a PV system, including a comprehensive comparison with its conventional power source counterpart, has remained unexplored. This research work therefore is intended to identify and specify an inductive load to be used on both conventional and PV solar system, with a view to draw conclusions on their performances

II. METHODS

A. Mathematical Modelling of the PV System Under Standard Test Condition in Simulink

This involve the determination of the number of series and parallel strings needed to achieve a desired power output at the rated voltage, assuming all losses to be negligible, peak solar intensity (PSI) to be 1kW/m^2, and temperature under standard test condition (stc) to be 25^0c. The relationship between number of series connected string (N_s), Peak-to-peak voltage (V_{pp}) and voltage at maximum power (V_{mp}) is given by the following expressions:

$$N_s = \frac{V_{pp}}{V_{mp}} \tag{1}$$

Where N_s represents the number of series string, V_{pp} is the peak-to-peak voltage and V_{mp} is the voltage at maximum power.

To determine the required number of PV array to be connected in parallel the expression in equation (2) is deployed

$$N_P = \frac{P_{out}}{N_s \, * P_{max}} \tag{2}$$

Where N_P represents number of parallel strings, P_{out} stands for output power, N_s is the number of series connected string and P_{max} is the maximum power

Expression for current and resistance are given in (3) and (4) as follows:

$$\text{Current (I)} = \frac{Power\ (W)}{Voltage(V)} \tag{3}$$

$$\text{Resistance } (\Omega) = \frac{Voltage}{Current} \tag{4}$$

The fill factor (FF) which indicates the quality of the PV cell, expressed as the ratio of the practical maximum power point and theoretical maximum power point is expressed in (5) as:

$$\text{FF} = \frac{P_{max}\,practical}{P_{max.theoriical}} = \frac{V_{mp\,x\,I_{mp}}}{V_{oc\,x\,I_{sc}}} \tag{5}$$

To determine the overall energy generation potential from the PV panel under standard test condition (stc) the expression in [51] is deployed as follows:
The overall Energy (E_{in}) from the PV is express as follows:

$$E_{in} = T_g * \alpha_{sc} * P_{sc} * \text{G} * A_{sc} \tag{6}$$

Where E_{in} is the overall energy of the PV module top surface, T_g represents the glass transmissivity, α_{sc} is the PV module absorptivity, P_{sc} is the packing factor of the solar panel, G is the Irradiation Intensity and A_{sc} represents the area of solar cell. The equivalent losses (E_l) by convection is given in (7) as follows:

$$E_l = U_{Sca}(T_{sc} - T_{amb.})\, A_{sc} \tag{7}$$

Where T_{sc} is define as:

$$T_{sc} = \frac{P_{sc} * \mathrm{G} * (T_g * \alpha_{sc} - \eta_{sc}) + (U_{sca} * T_{amb.} + U_t * T_{bs})}{(U_{Sca} + U_t)} \tag{8}$$

T_{sc} is the Solar cell temperature, T_{bs} is the surface temperature of the module, U_t is the total heat transfer co-efficient,U_{sca} is the total heat transfer from the top to ambient of the system, η_{sc} is the PV module reference electrical efficiency.

The Energy from the PV (E_{pv}) is express as follows:

$$E_{pv} = \mathrm{G} * T_g * \eta_{sc}\, [1-\mu_{sc}(T_{sc} - T_r)] \tag{9}$$

Where T_g is the transmittance of the PV surface, T_r is the reference temperature at which the module is tested (25^{0c})

The expression in (10) depicts the PV output converted to electrical energy (E_e) as follows:

$$E_e = \eta_{sc} * P_c * \mathrm{G} * A_{sc} \tag{10}$$

The remaining portion of the PV output is converted into thermal energy as shown by the following expression:

$$E_t = U_t\, (T_{sc} - T_{bs}) \tag{11}$$

The overall energy balance equation for the PV module (E_{in}) is express as follows:

$$E_{in} = E_l + E_e + E_t \tag{12}$$

B. Modelling of a 20.515kW PV System

The above equations (1 to 12) where taken into appropriate consideration during the design of a 20.5 kW PV system to determine the required output power based on user defined module the following specifications as shown in table 1, were used to model the PV system:

Table 1: PV module parameters specifications

Number	Component Description	Rating
1	Maximum power (P_{max})	10W
2	Open circuit voltage (V_{oc})	21.5V
3	Voltage at maximum power (V_{mp})	17.7V
4	Short circuit current (I_{sc})	0.65A
5	Current at maximum power (I_{mp})	0.57A
6	Inverter output voltage	$400V_{rms}$

Therefore, voltage at maximum power (V_{mp}) = 400 * $\sqrt{2}$

$$V_{pp} = 566V_{max}$$

Therefore, (1) is deployed to obtain the required number of PV array to be connected in series to give the required output power:

$$N_s = \frac{566}{17.7} = 32$$

Therefore 32 PV arrays will be required to be connected in series, also to determine the number of arrays to be connected in parallel (2) will be followed:

$$N_P = \frac{P_{out}}{N_s * P_{max}}$$

Given required power output (P_{out}) to be 20515W, series connected string (N_s) = 32, and Maximum power (P_{max}) = 10W therefore, the number of parallel connected string will be determined as follows:

$$N_P = \frac{20515}{32*10} = 64$$

Therefore, 64 parallel string is required to give the desired output power. The following expression is used to calculate the required resistance:

$$\text{Given that current (I)} = \frac{Power\ output}{voltage}$$

$$\text{I} = \frac{20515}{400} = 51.29\text{A}$$

The resistance can be calculated using ohms' law which is express as $\text{R} = \frac{V}{I}$

$$\text{R} = \frac{400}{51.29} = 8\ \Omega$$

The above values where inputted into the appropriate fields in Simulink and visualized using graphical plots, this gives a total power output of 20515W. Summary of the PV parameters specifications are given in table 2 as follows:

Table 2: Determined values and parameters of the PV system

Number	Component Description	Value
1	Vpeak	566V_{max}
2	Numbers of series connected string	32 strings
3	Numbers of parallel connected string	64 strings
4	Calculated value of current	51.29A
5	Calculated value of resistance	8Ω
6	Required output from PV	20.515kW

C. Modelling of Asynchronous Machine under Different Load Conditions

The optimal performance and efficiency of asynchronous machine also known as an induction motor, was ascertained by testing it under different load conditions. This was done by varying the load torque at different time ranges. The expression in (6) provides a detailed illustration of how the parameters of the asynchronous machine can be modelled under different load conditions. Table 3 presents the summary of specifications used in modelling the asynchronous machine in Simulink software.

Table 3: Specifications of the Asynchronous Machine Parameters

Number	Parameter	Value
1	Input power of the motor	(7.5kW)
2	Motor input voltage	400V
3	Frequency	50Hz
4	Motor speed	1460RPM
5	Mechanical input	Torque (Tm)
6	Mechanical power	20515W
7	Stator resistance	0.2147 Ω
8	Stator inductance	0.991mH
9	Rotor resistance	0.2205 Ω
10	Rotor mutual inductance	64.19mH
11	Inertia(J)	$0.102(\text{Kg.m}^2)$
12	Friction factor(F)	0.009541 (N.m.s)
13	Number of Pole pairs	2
14	Initial condition	0000

The relationship between the load torque (T_l) or shaft torque T_{sh} in Nm, power output (p_{output}) in (W) and angular velocity (ω)in rad/secs is given by

$$T_l \text{ or } T_{sh} = \frac{p_{output}}{\omega} \quad (13)$$

The expression for the motor power is derived by the following relationship

$$p_{output} = T_{sh} * \omega \tag{14}$$

Where motor output power is given as 7500w, and angular velocity is defined by the following expression

$$\text{Angular velocity } (\omega) = \frac{2*\pi*N}{60} \tag{15}$$

Where the value of π in radians is given as 3.142 and speed of the asynchronous motor = 1460RPM. The angular velocity can be calculated as follows

$$\text{Angular velocity } (\omega) = \frac{2*\pi*N}{60}$$

The load torque was determined under different conditions following (13) as

$$T_l \text{ or } T_{sh} = \frac{p_{output}}{\omega} = \frac{2*\pi*1460}{60}$$

Given the motor output power to be 7.5kW and ω = 153rad/secs, the full load torque can be calculated

$$T_l = \frac{7500}{153} = 49\text{N-m}$$

Shown in table 4 is the summary of the of the result obtained by the combination of the above expressions:

Table 4: Summary of the asynchronous model parameters

Number	Asynchronous machine parameters	Value
1	Motor output power	7.5kW
2	Angular velocity (ω)	153rads/secs
3	Load torque	49 N-m
4	π in radians	3.142

Shown in table 5 is the calculated values of the load torque of the asynchronous machine rated 7.5kW

Table 5: Load torque of the asynchronous machine rated at 7.5kW

S/N	Loading condition in seconds	Load torque (T_L) in N-m on the motor rated at 7.5kW and speed of 1440 RPM
1	T_L at 1 seconds = T_L	49.7
2	T_L at 2 seconds = $T_{L/2}$	24.9
3	T_L at 3 seconds = $T_{L/3}$	17
4	T_L at 4 seconds = $T_{L/4}$	12.4

An innovative comparative method was employed to investigate the overall performance of the asynchronous machine when powered by a PV system. The asynchronous machine was tested under various load conditions at pre-determined time intervals. The following machine parameters were studied which includes: waveform of the electromagnetic torque signal, motor speed signal, the stator and rotor current across the three phases of the asynchronous machine using Simulink simulation software, graphs were generated to analyze and comprehend the trends exhibited by these signals. The Matlab/Simulink models for PV system and conventional power source, supplying the load are shown in Figures 1 and 2.

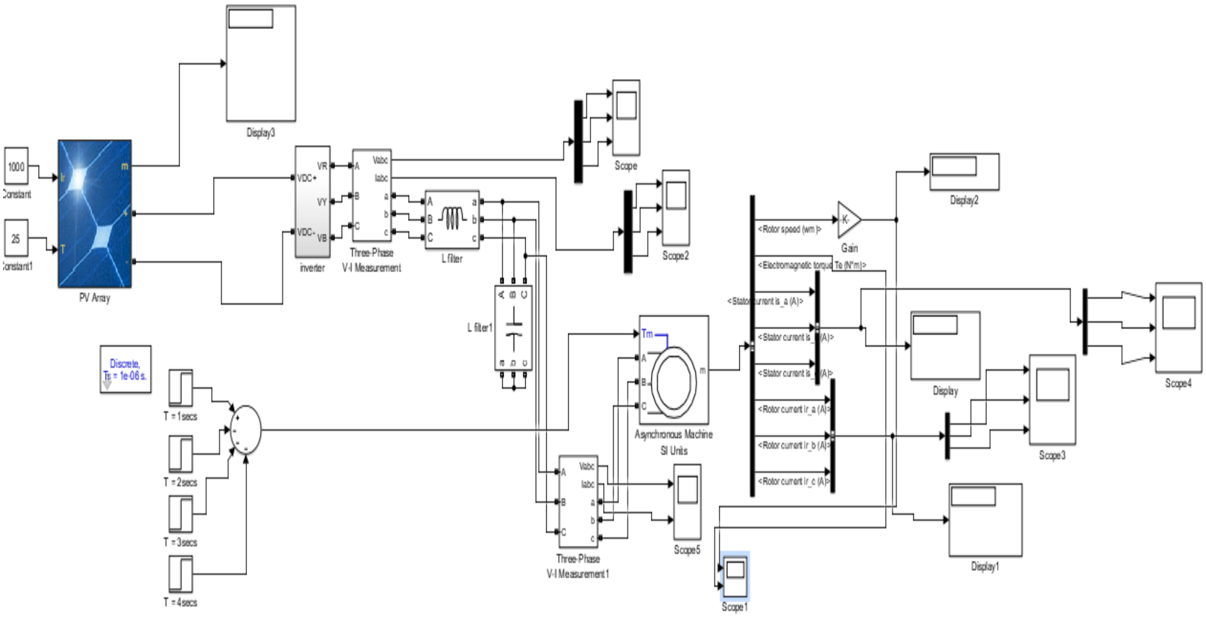

Figure 1: Model of the PV System supplying Inductive Load

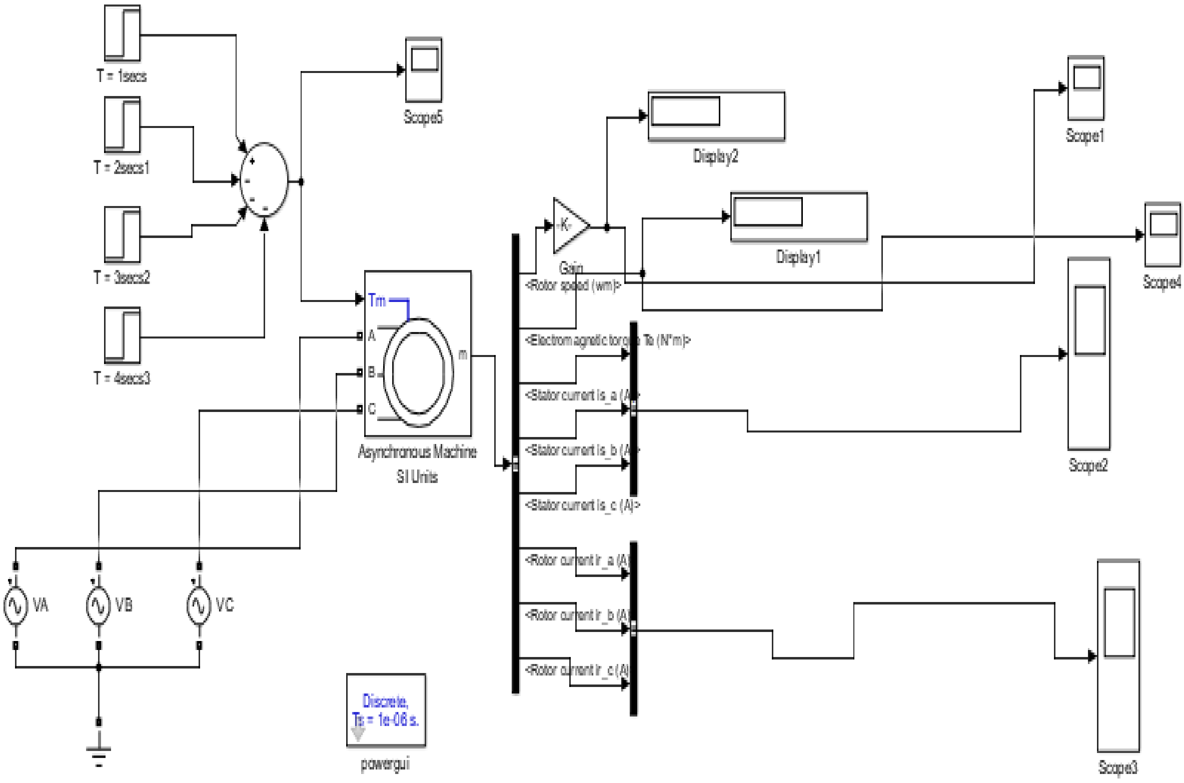

Figure 2: Model of the Conventional Source supplying Asynchronous Machine

III. RESULTS

Analysis of performances was done on asynchronous machine rated at 7.5kW to determine the performance and efficiency of the PV system and the conventional source. The following parameters of the asynchronous motor were compared which includes the rotor speed, rotor current, and rotor torque signal waveform for the two sources (conventional source and PV system) presented as follows:

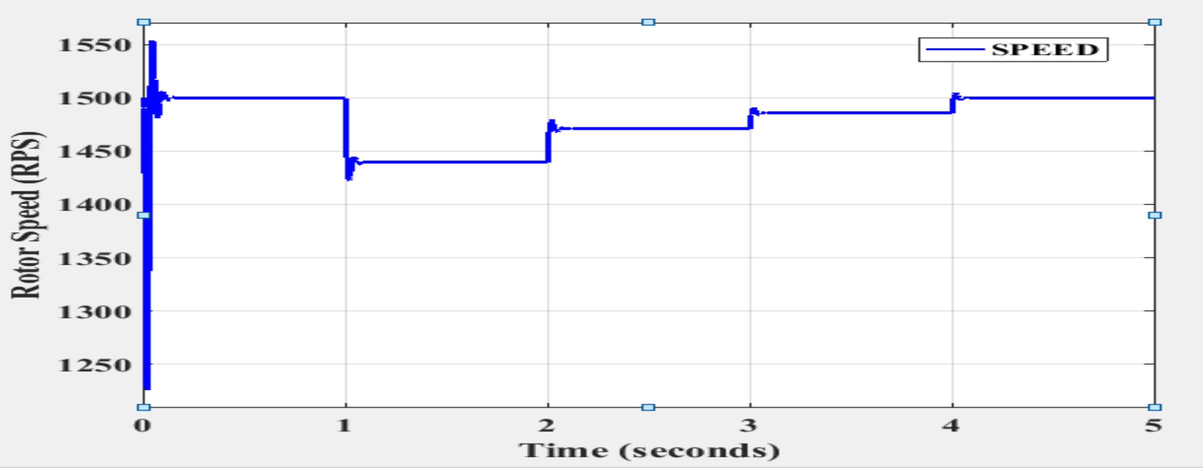

Figure 3: Rotor speed rated at 7.5kW from conventional source

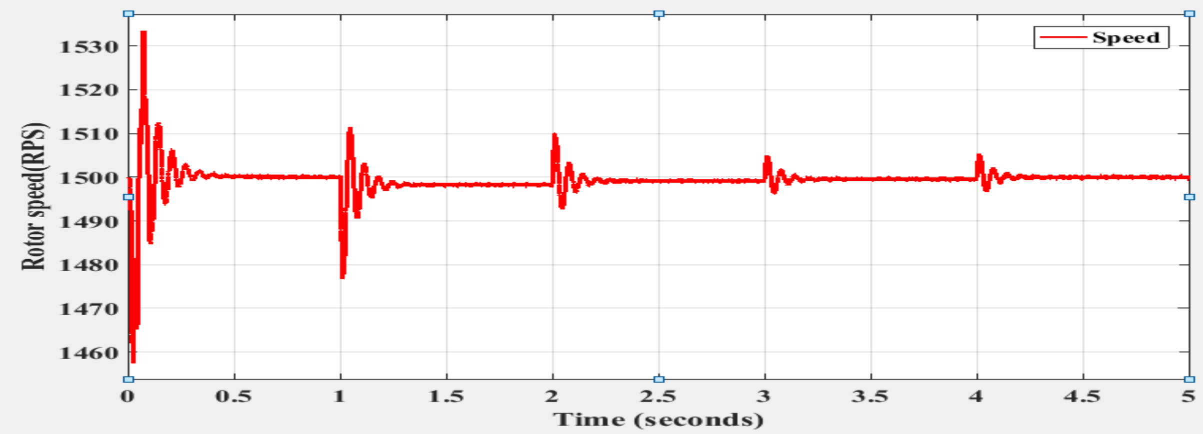

Figure 4: Rotor speed rated at 7.5kW from PV system

The outcome showed that 7.5kW asynchronous machine rated capacity, the stability of the machine is greatly improved as the toggle in the rotor speed signal waveform reduced abruptly when sourced from PV system. The rotor current of the asynchronous machine rated at 7.5kW when serve from both sources are presented as follows:

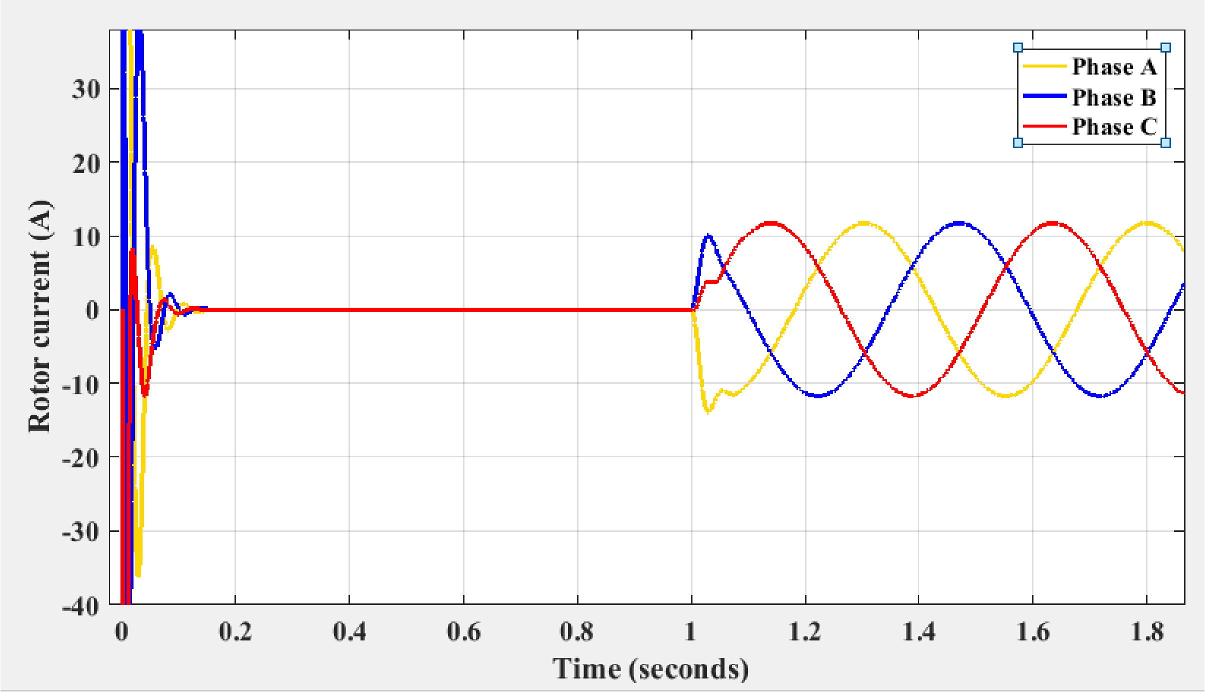

Figure 5: Three phase rotor current of the machine rated at 7.5kW from conventional source.

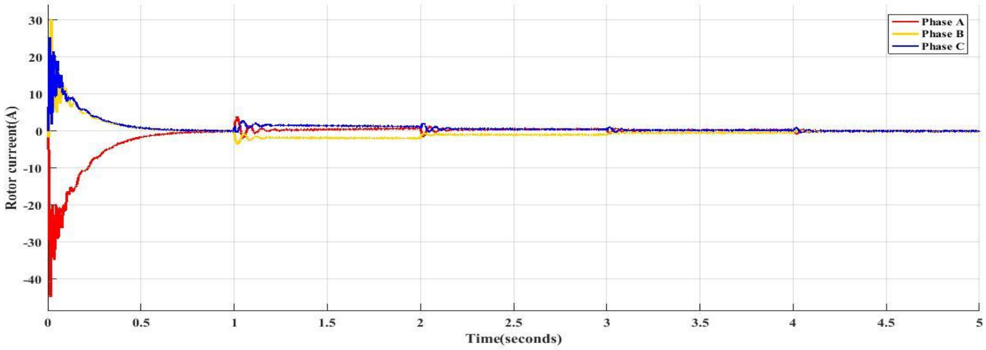

Figure 6: Three phase rotor current of the motor rated at 7.5kW from PV system

The stability of the rotor current is greatly improved with 7.5kW capacity of the asynchronous machine when powered with PV system.

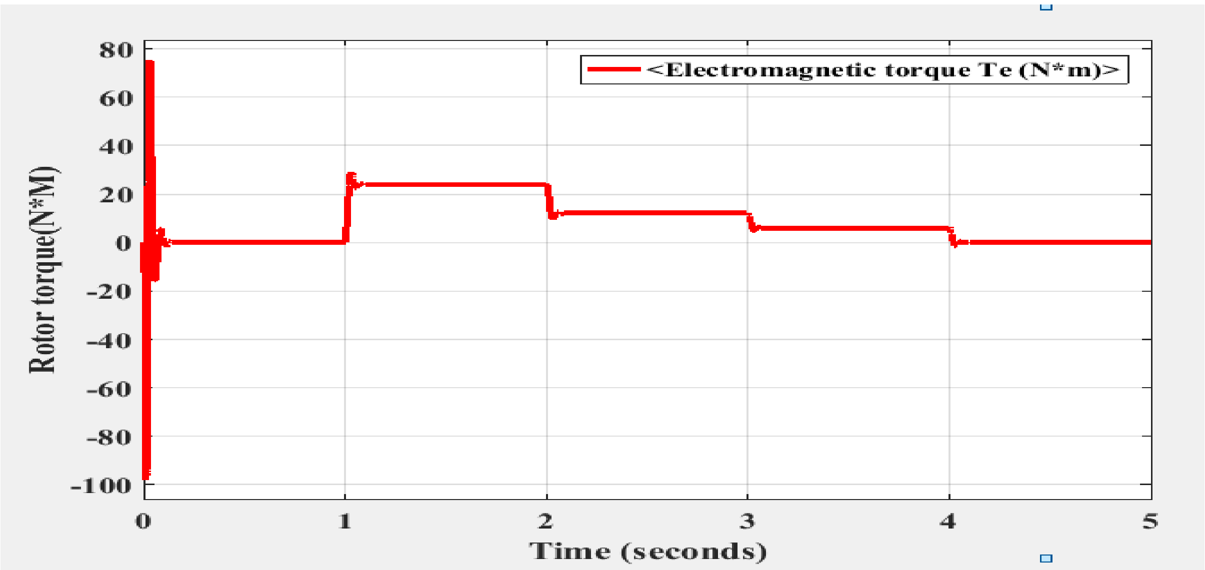

Figure 7: Electromagnetic torque of the motor rated at 7.5kW from conventional source

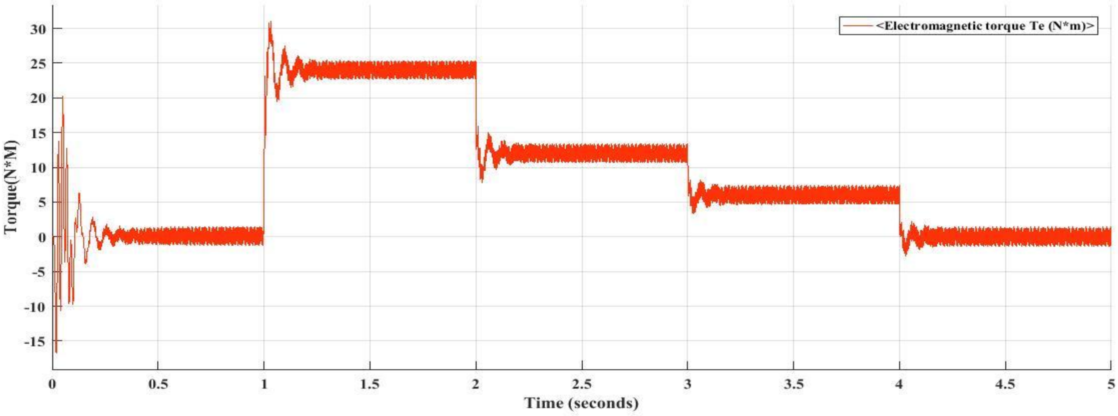

Figure 8: Electromagnetic torque of the motor rated at 7.5kW from PV system

The simulation results as seen from the scope block showed a significant improvement in the stability of the electromagnetic torque of the motor rated at 7.5kW when powered conventional source than PV source.

IV. CONCLUSION

The comparison carried out on the performance of inductive load on PV system and conventional electric power source, showed that there is a significant reduction in harmonics, efficiency and stability of the asynchronous machine output when powered with the three-phase conventional electric power source compared to its performance when powered from PV system. The study showed that the PV system have significant impact on inductive loads than the conventional source since the conventional source is more robust, have stable AC current supply and minimal harmonics distortions compared to the PV system. Therefore, to achieved a greater efficiency with the PV system, advance strategies on how to remove the generated low frequency in the process of converting D.C to A.C needs to be carefully considered. Also, increasing the power rating of the solar panel and battery capacity will improve the length of usage and optimal performance of the PV system during raining season or days with cloudy weather condition.

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