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Performance Evaluation of Induction Motor Behaviour on Conventional and PV System Power Sources

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ABSTRACT: The present study explores the integration of photovoltaic (PV) systems for enhancement of power system quality and reliability, particularly when PV system is deployed to power inductive loads which have wide applications in commercial and industrial settings. A mixed approach is deployed using MATLAB/Simulink for the modelling and simulation process. The study investigates the impact of inductive loads on PV system, comparing its performance with a conventional power source of same power willing capacity. The PV system was modelled by connecting PV arrays in series and parallel combinations. The output of the PV arrays was fed into a three phase PWM inverter, the harmonics present at the inverter output were eliminated using properly sized Inductor- capacitor (L-C) filter circuit. Also, a three-phase conventional source of same output capacity was modelled. Comparative analysis of the impacts inductive loads has on both sources were carried out and this was accomplished by integrating three-phase asynchronous motor rated at 15kW(20HP). The induction motors were independently powered by two distinct sources and further subjected to intermittent loading conditions. The major parameters investigated includes the rotor speed, rotor current, and electromagnetic torque of the asynchronous motor. The outcome of the study showed that the conventional source outperforms the PV system. These necessitates the studies on adoption of advance strategies on how the negative impacts and challenges encountered in the course of integrating PV system to power inductive loads will be address.

KEYWORDS: Asynchronous Machine; Rotor Current; MATLAB/Simulink; Rotor Speed; Electromagnetic Torque; PV Array, Conventional Source; Photovoltaic System; L-C filter.

I. INTRODUCTION

Depletion of fossil fuels and the increasing energy requirements have spurred the exploration of alternative and additional sources of electrical energy. Non-conventional energy sources seem to be the remedy to this malady, especially in situations where conventional power generation and transmission are impractical or expensive. In such cases, it is pertinent to maximize the efficiency of power generation from non-traditional sources to meet the power needs effectively (Sakshi, Roshan, & Anupam, 2017; Yang, Li, Peng, Wagner, & Mauzerall, 2018). Solar energy is relatively abundant in nature and environmentally friendly since it does not support combustion. PV systems also have minimal operation cost; therefore, it serves as a good alternative to mitigate the tremendous negative impacts conventional power sources that emits greenhouses gasses have on the atmosphere and the environment at large (Anyaehie, 2011). The deployment of PV system to power induction motors in commercial and industrial settings is a complex task but it has numerous accompanied benefits. Particularly, in remote locations and areas with erratic power supply from the main grid. Such limitations in power availability to supply inductive loads have informed the decision of many researchers to source for alternative energy (Ali, 2016). Several environmental factors influence the power quality harnessed from PV systems which includes the irradiance level, panel aging, orientation, temperature, wind, and humidity. These factors make the output power from the solar panel inherently intermittent (Nurul, Ajisman, & Amad, 2016; Song, Liu, & Yang, 2021). The reliability of the power system when inverter-based generator (IBGs) gains dominance over synchronous generators is still a major concern to power engineers (Mohammed, Alhelou, & Bahrani, 2023). The study by (Zhou, Zhang, Kathriarachchi, Dennis, & Goyal, 2022; Manoj & Kumar, 2021; Rathnayake, et al., 2021) examined the technical complexities associated with the grid forming inverters (GFM) and inverter-based generators (IGBs), focusing on enhancement of system strength and penetration of renewables. Inductive loads such as induction motors been an alternating current electric motor that relies on electromagnetic induction between the stator and the rotor to generate mechanical torque without direct electrical connections have high power requirement. To minimize technical issues and grid disturbance (Nkan et al, 2020), assessed contingencies, aimed at stabilizing and improving the grid supply. As AC power applied to the stator establish a rotating magnetic field, which align with the rotor's magnetic field, a relative motion is established, but due to the resulting speed difference between the stator and rotor, the misalignment results in the generation of electromagnetic torque leading to mechanical rotation of the rotor couple to a shaft to drive connected loads. Induction motors comes either in single or three phase versions, where the single phases are commonly used for powering small appliances in residential and commercial settings. Capacitors are used to create a phase displacement of 120^0 between the windings in single phase induction motors, by splitting the phase. On the other hand, the three-phase induction motors have a balance rotating magnetic field with 120^0 phase angle displacement between each phase. These motors are commonly used in various industrial applications, particularly for driving heavy loads, they come in two primary types namely: squirrel cage type and wound rotor types. Studies by (Bhateja, Nguyen, Nguyen, Satapathy, & Le, 2017), investigated the performance of DC mini grid system using photovoltaic module, incorporating boost converter with maximum power point tracker (MPPT) to enhance efficient power supply. The outcome showed that the ripples present in resistive loads are less compared to inductive loads, PSIM software was deployed for validation of the model. An accurate model for induction motors was developed, with a major focus on voltage behind reactance (VBR) the model was implemented in MATLAB/Simulink, the outcome showed a significant improvement in computational efficiency, enabling precise estimation of various motor parameters and enhancement of the interface with external controllers for improved motor analysis and control (Manekar & Bodkhe, 2013). The economic growth and development of any nation are intrinsically tied to the availability of energy (Omorogiuwa and Okpo, 2015). In enhancing sustainability in power grid usage, dominated by synchronous generators, referred to conventional source, (Nkan et al, 2019 and Natala et al 2023) worked extensively on application of FACTS devices application, aimed at grid adaptability to inductive loads.

Access to a reliable electricity supply plays a pivotal role in empowering individuals and facilitating personal and economic development. Performance evaluation of asynchronous motor was conducted in (Okpo et al, 2019). An innovative approach to dynamic modelling of induction motors, using a modular Simulink model was studied by (Shah, Rashid, & Bhatti, 2012), they explored the machine internal variables and the various algorithm without the need for estimators, this makes Simulink a valuable tool for both educational and research purposes in the field of electrical machine drive. The study carried out by (Sangeetha & Parthiba, 2014), discussed the efficiency of reference frames in analyzing electrical performance and presents a comprehensive guide for implementing a three-phase induction motor model in Simulink focusing on its stator and rotor equations in the stator reference frame. The research aims to simulate the rotor behavior in MATLAB/Simulink while investigating the impact of speed, torque and rotor currents on its performance with a particular focus on future investigation into flux saturation and harmonic on the supply side. Multi-type FACTS controllers for power sustainability and adaptability to inductive loads was assessed (Nkan et al, 2021). Comparative analysis of the predicted transient torque and the speed in three phase induction motor models was carried out by (Okoro, 2002; Ramprasath & Manojkumar, 2015), the study focused on comparing a conventional model with one that accounted for skin and saturation effects during motor model development. Qualitative and analytical method were employed to access the impact of rotor and stator slots with harmonics in the winding. The present study is therefore significant as it will carry out a novel comparison on the performance of induction motors when powered from two distinct sources of same capacity particularly, with a major focus on the conventional source and the PV system, so as to investigate the impacts the sources have on behavior of the motor parameters. Due to wide application of induction motors and its continuous usage in commercial and industrial settings, alternative power sources to supply such loads is needed with careful justifications. The remaining part of this paper is organized as follows: section II will present the methods adopted in the present study, section III will cover the simulations results and discussion, while section IV will give conclusion of the study and finally section V will present the recommendations.

II. METHOD

This section elaborates on the methods deployed to implement the models and their respective subsystems in Matlab/Simulink, it explains the systematic approach used to carry out a novel comparison on the performance of inductive loads when powered from two distinct sources namely the conventional source and the PV system, the overall concept followed during the modelling process is detailed as follows:

A. Asynchronous Machine Powered from Conventional Source

The analysis of Asynchronous machine parameters commenced with the development of the mathematical model using a three-phase conventional source with output power rating of 20.5kW in Matlab/Simulink version R2016a. The modelling process incorporated the utilization of various mathematical expressions to calculate the maximum equivalent DC voltage supplied to each phase. The expression in eq.1 is used to determine the maximum output voltage presented as follows:

$$Maximum\ Voltage\ (V_{max}) = \frac{\sqrt{2} * V_{rms}}{\sqrt{3}} \quad (1)$$

Given V_{rms} under worst condition to be 400V, the equivalent DC voltage required from each phase is given as:

$$V_{max} = \frac{\sqrt{2}*400}{\sqrt{3}} = 326.54V$$

Conventional power source was modelled to serve the asynchronous motor rated at 15kW , the reactive power was determined by applying the power triangle formula, the per phase voltage at worst case scenario is determine as follows:

$$V_{ph} = \frac{400}{\sqrt{3}} = 230.9V \quad (2)$$

The expression for the real power is given by the following expression:

$$P = VIcos\phi \quad (3)$$

With P defined as the output power of the three-phase asynchronous motor, V representing the phase voltage and θ is the phase angle difference between the voltage and current. The current drawn by the motor is calculated as follows:

$$I = \frac{P}{Vcos\theta} = \frac{15000}{230 * 0.85} = 76.73A$$

$$cos^{-1}(0.85) = 31.8^0$$

$$Q = VIsin\theta \quad (4)$$

$$Q = 230 * 76.73 \sin(31.8^0) = 9.299\text{kVar}$$

Where Q is defined as the reactive power in kVar.

The asynchronous motor voltage in time domain and in frequency domain are represented respectively as follows:

$$V = -\frac{Nd\phi}{dt} \quad (5)$$

$$V = -Nj\omega\phi(\omega) \quad (6)$$

The voltage can also be represented as:

$$V = -j\omega LI \quad (7)$$

V represents the induced voltage in the rotor windings, N is the number of turns, ϕ is the linkage flux, t is time in seconds, L is the inductance in henry, I is the current and ω represent the angular frequency. The above expressions were appropriately considered during the modelling process of the conventional source used to supply the asynchronous motor.

Presented in fig. 1 is the model of the conventional source supplying the induction machine.

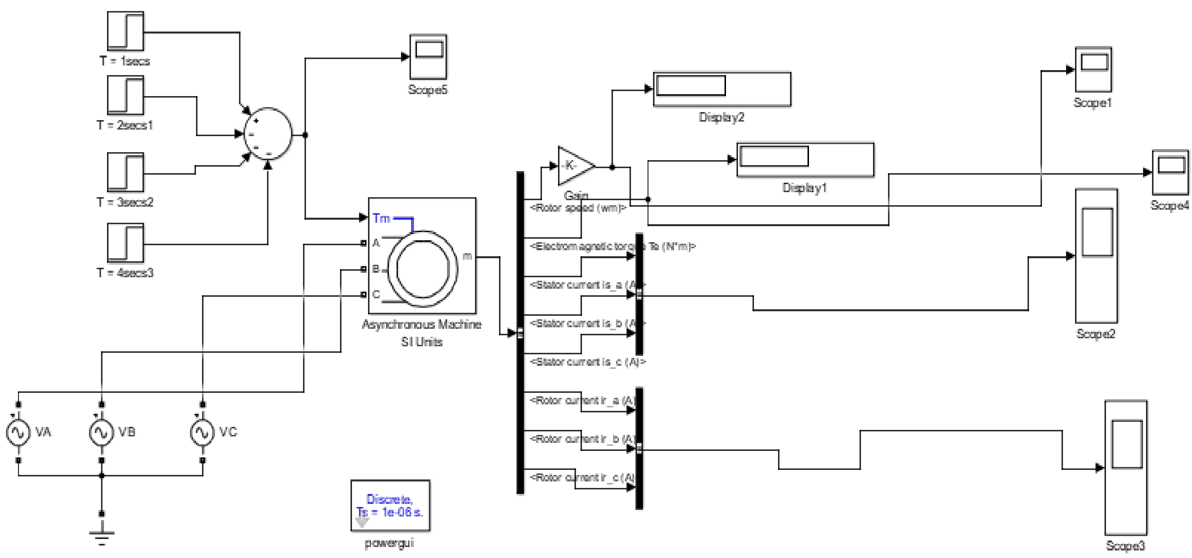

Fig. 1: Asynchronous machine powered from three phase conventional source.

B. Sizing of the PV System

In order to model the PV system to give a specific desired power output in Simulink, the user defined module was deployed. The required power output from the PV arrays was determine by calculating the number of series and parallel connected string under standard test condition (STC) with approximately estimated peak solar intensity (PSI) of $1kW/m^2$ and a cell temperature of 25^0C. To determine the number of PV arrays to be connected in series and parallel, the following mathematical relations were considered during the modelling process, the number of arrays to be connected in series is determined as follows:

$$N_s = \frac{V_{pp}}{V_{mp}} \tag{8}$$

Where N_S is defined as the number of series string, V_{PP} is the peak-to-peak voltage and V_{mp} represent the voltage at maximum power. The number of parallel strings is determined as follows:

$$N_p = \frac{P_{out}}{N_s * P_{max}} \tag{9}$$

Where N_p is the number of parallel strings, P_{out} represents the output power and P_{max} represent the maximum power from the PV array.

The fill factor (FF) that shows the quality of the PV cell, given as the ratio of the practical maximum point and theoretical maximum power point is express as follows.

$$FF = \frac{P_{max}Practical}{P_{max}Theoritical} = \frac{V_{mp} * I_{mp}}{V_{oc} * I_{sc}} \tag{10}$$

The system in fig. 2 is a representation of the simulation model of the PV array in Simulink.

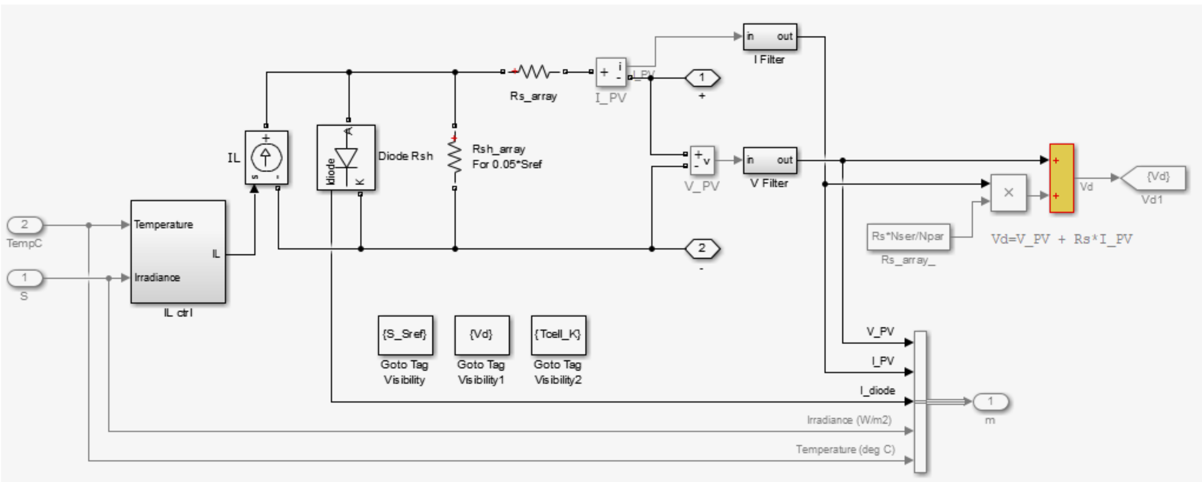

Fig. 2: Model of the PV array

C. Inverter Circuit

The solar panel generates DC power, which necessitates conversion to AC for driving inductive loads. This conversion process involved an inverter circuit which consist of MOSFETS, a sine wave generator, input and output blocks, resistors, capacitors, and logic function blocks. The MOSFETs input gate received pulses from the sinewave generator, resulting in a pulse width modulated wave (PWM) at the inverter three phase output. To enhance optimal performance of the asynchronous motor, a pure sine wave and a balance three phase voltage must be applied to the stator. A suitably sized filtration circuit was deployed to eliminate the PWM inverter output ripples. Shown in fig. 3 is the model of the inverter circuit.

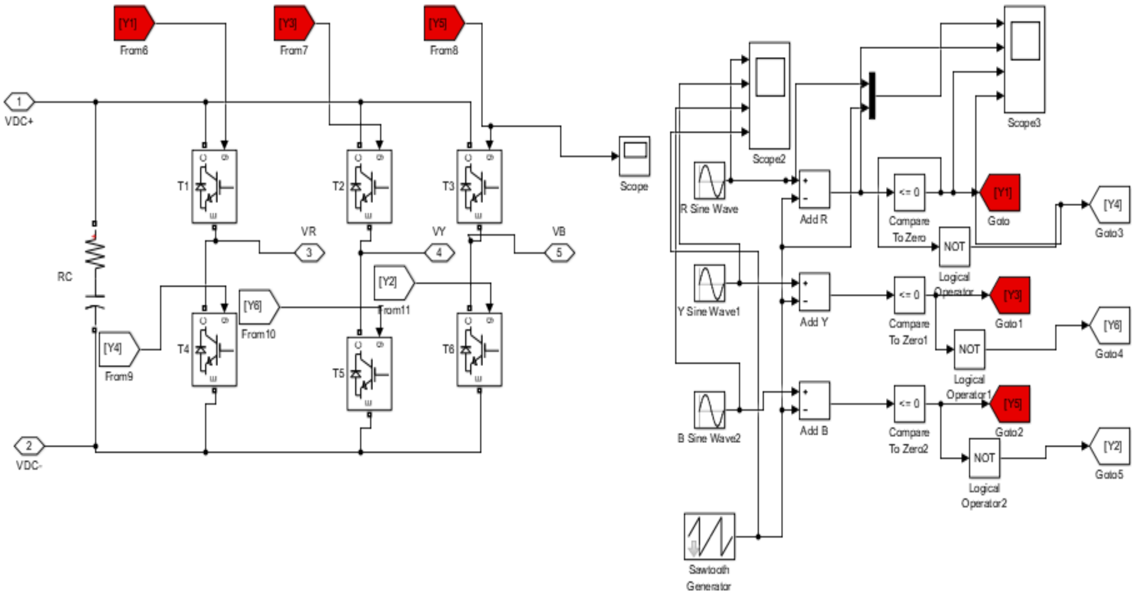

Fig. 3: Modelling of the Inverter Circuit

D.Simulation Model of the PV System Supplying the Asynchronous Motor

The modelling of the PV system to power the asynchronous machine began with proper sizing of PV system to generate same power output as that of the conventional source counterpart, followed by the integration of three phase PWM inverter circuit. The output of the inverter circuit was passed through L-C filter to eliminate the ripples present during the process of conversion of DC to AC. Three phase asynchronous motors rated at 15kW was powered by the 20.5kW PV system so as to investigate the impact on the motor parameters. The complete model of the asynchronous motor when powered from a PV system is presented in fig. 4 as follows:

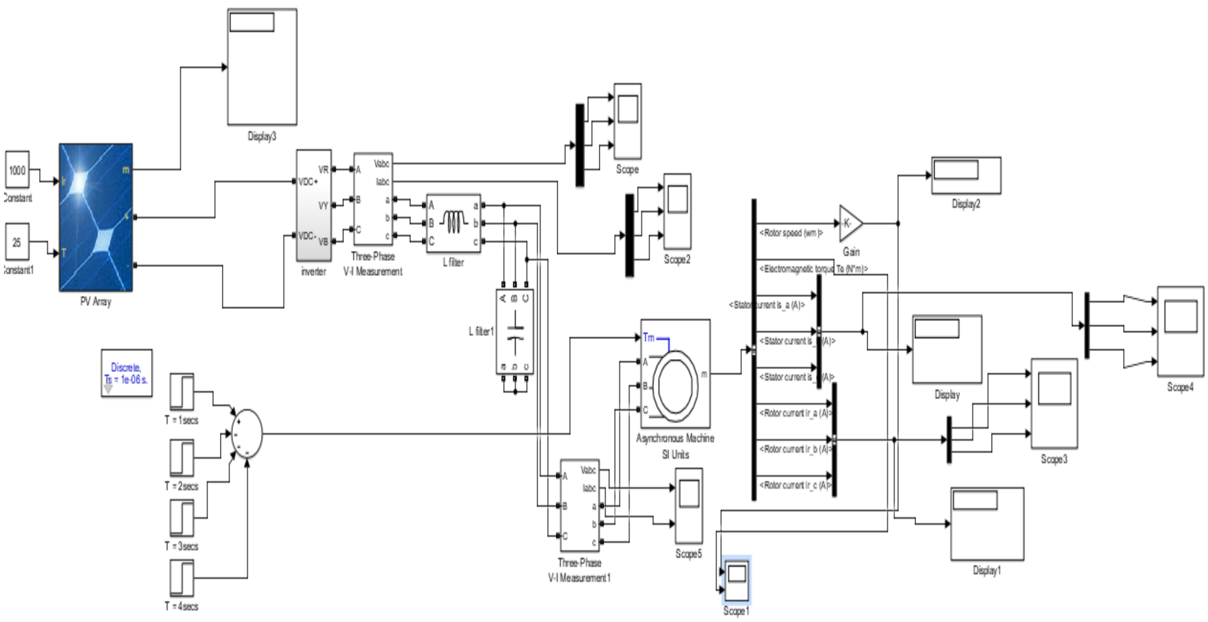

Fig. 4: Model of the PV System Supplying Inductive Load

E. Modelling of the Asynchronous Machine

The simulation was carried out on asynchronous motors rated at 15kW, the motor was powered from two distinct sources having same power willing capacity and subjected to intermittent loading, so as to examined the behavior of the parameters when powered from the two distinct sources. presented in table 1 are the parameters deployed during the modelling process of the asynchronous machine rated at 15kW.

Table 1: Specifications of the Asynchronous Machine Parameters

Number	Parameter	Value
1	Input power of the motor	20Hp or 15kw
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	0.000991H
9	Rotor resistance	0.2205 Ω
10	Rotor mutual inductance	0.06419H
11	Inertia(J)	0.102(Kg.m^2)
12	Friction factor(F)	0.009541 (N.m.s)
13	Number of Pole pairs	2
14	Initial condition	0000

The load torque is determined by the following expression:

$$T_l = \frac{P_{output}}{\omega} \tag{11}$$

The motor output power is express as follows:

$$P_{output} = T_l * \omega \tag{12}$$

Shown in table 2 is the summary of the parameters of the asynchronous motor rated at 15Kw.

III. RESULTS

The determined parameters during the modeling process of the PV array under standard test condition (STC) is presented in table 4 as follows:

Table 4: Determined Parameters of the PV array

Number	Required Parameters	Value
1	Irradiance	1kW/m^2
2	Number of parallel strings	64
3	Number of series connected modules per string	32
4	Number of cells per module	60
5	Short circuit current (Isc)	0.65A
6	Open circuit voltage (Voc)	21.5
7	Current at maximum power (Imp)	0.57A

8	Temperature coefficient of short circuit current (Isc)	0.102^{0}c
9	Temperature coefficient of open circuit voltage (Voc)	-0.36099^{0}c
10	Voltage at maximum power (Vmp)	17.7V
11	Solar cell maximum power	10.089W

The graphical model that shows the power output generated from the PV array, at 1kW/m^2 irradiance and temperature of 25^{0}C is presented in fig. 5:

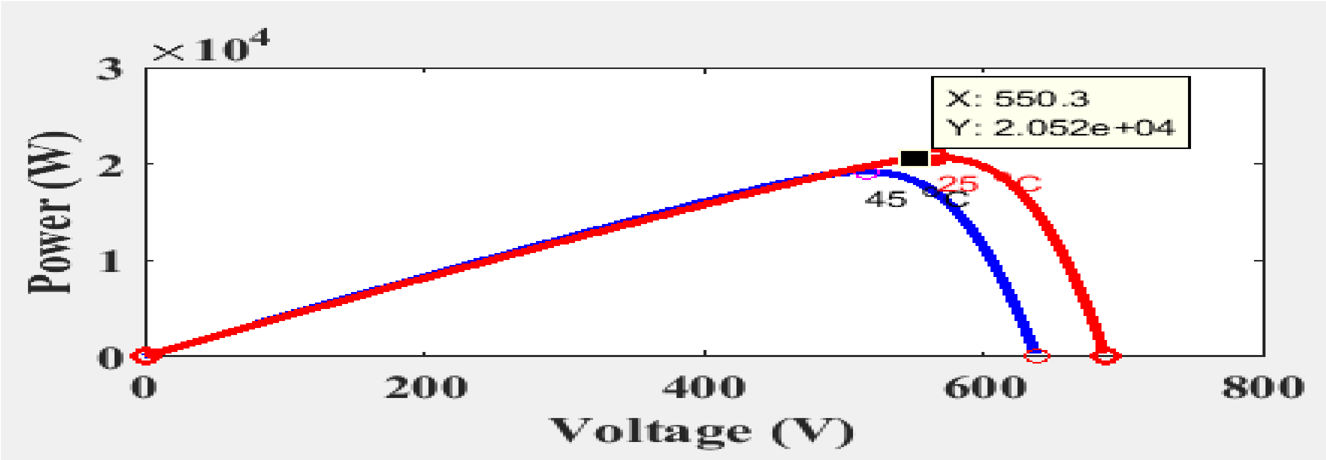

Fig. 5: Power and voltage generated from the PV system

The power output recorded by the combination of series and parallel string gives 20.5kW at 25^{0}C temperature with maximum output voltage of 550VDC. Fig. 6 presents the three phase output voltage waveforms from the inverter.

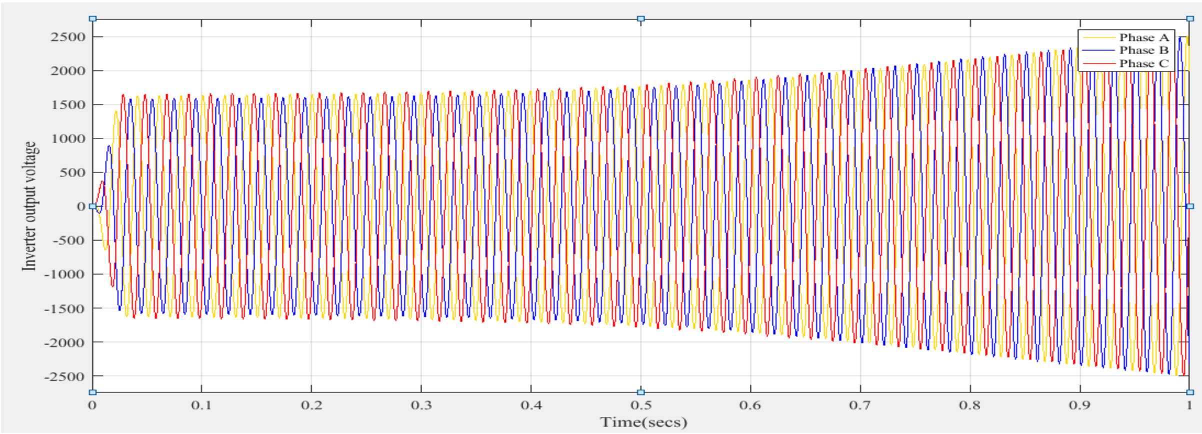

Fig. 6: Three phases inverter voltage waveform

The process of DC conversion to AC produces harmonics that generate heat and noise in the induction machine, appearing in the form of ripples, such ripples appear at the inverter output before filtration. Figs. 7 and 8 shows the distortions in the rotor and stator output waveform of the asynchronous motor before filtration.

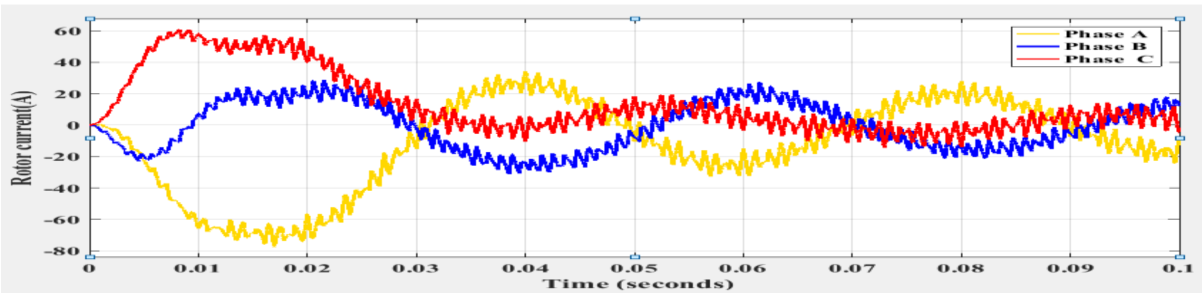

Fig. 7: Rotor current signal waveform before filtration

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The output signal waveform suffers from so much distortions due to presence of harmonic component that generate lower frequency during the process of converting DC to AC. The output signal waveform of the stator current before filtration is represented in fig. 8 as follows:

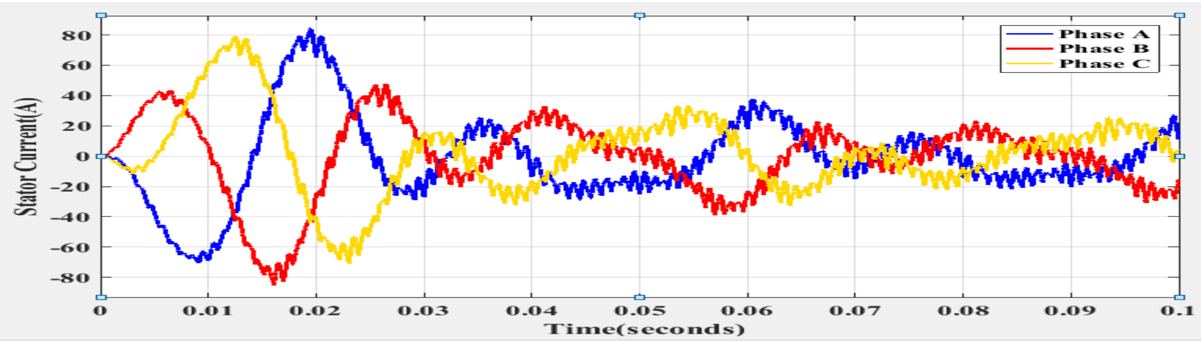

Fig. 8: Stator current of the asynchronous motor before filtration

The ripples present in the stator current waveform is significant due to effects of harmonics. These distortions were eliminated by connecting properly sized capacitors across the three phases in parallel and inductors across the three phases in series at the output of the inverter. Fig. 9 represent the output voltage signal waveform after the filtration process as follows:

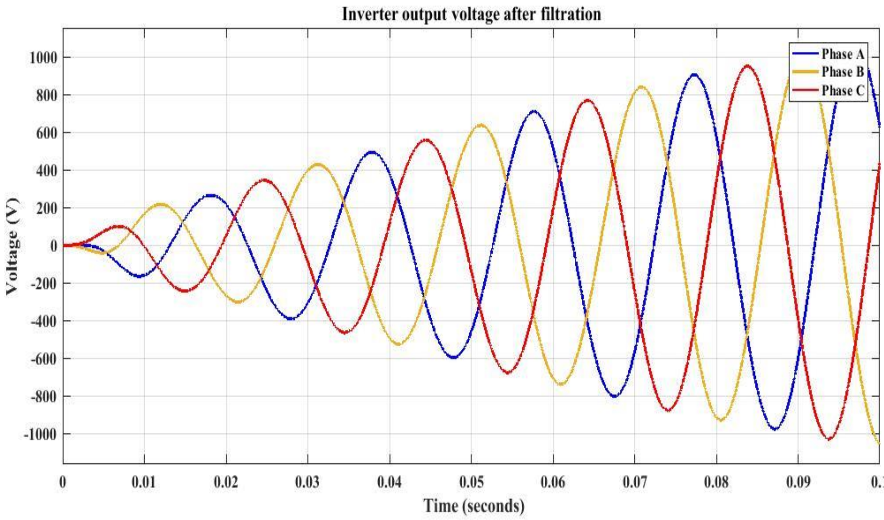

Fig. 9: Inverter output voltage signal waveform after filtration

The ripples were eliminated after the filter circuit was introduced.

A. Evaluation on the impacts of the asynchronous motor parameters when supplied by two different power sources (conventional and PV system).

In order to investigate the impact that PV systems have on inductive loads performances, two distinct power sources were employed to separately drive asynchronous motor with output power ratings of 15kW under varying load conditions. A comprehensive examination of the impact on the machine parameters was conducted by comparing the performance of both power sources. The analysis focused on key parameters, including rotor current, electromagnetic torque of the rotor, and rotor speed. Figs. 10 and 11 shows the rotor speed of the asynchronous motor rated at 15kW when powered from both sources.

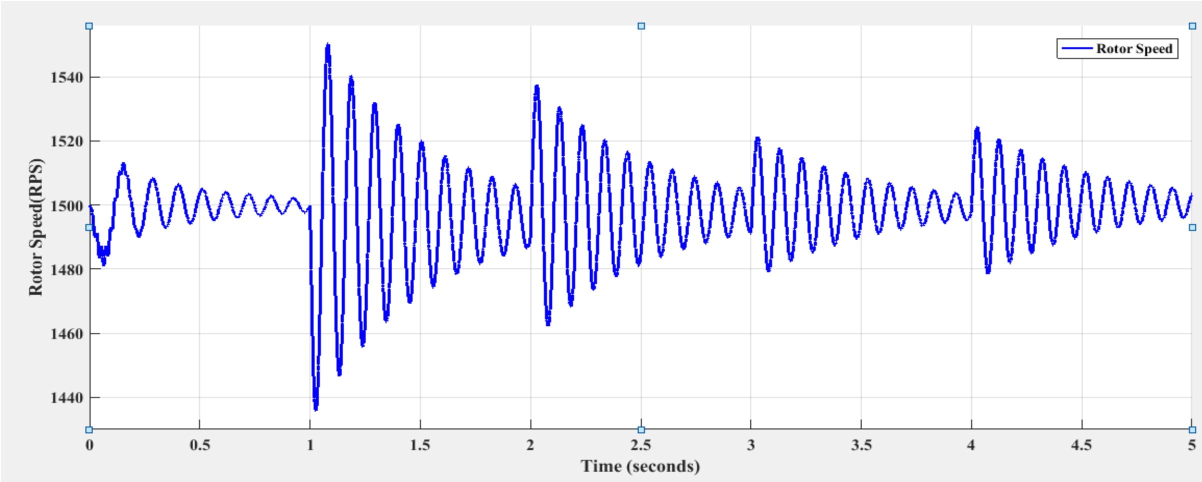

Fig. 10: Rotor speed at 15kW from PV system

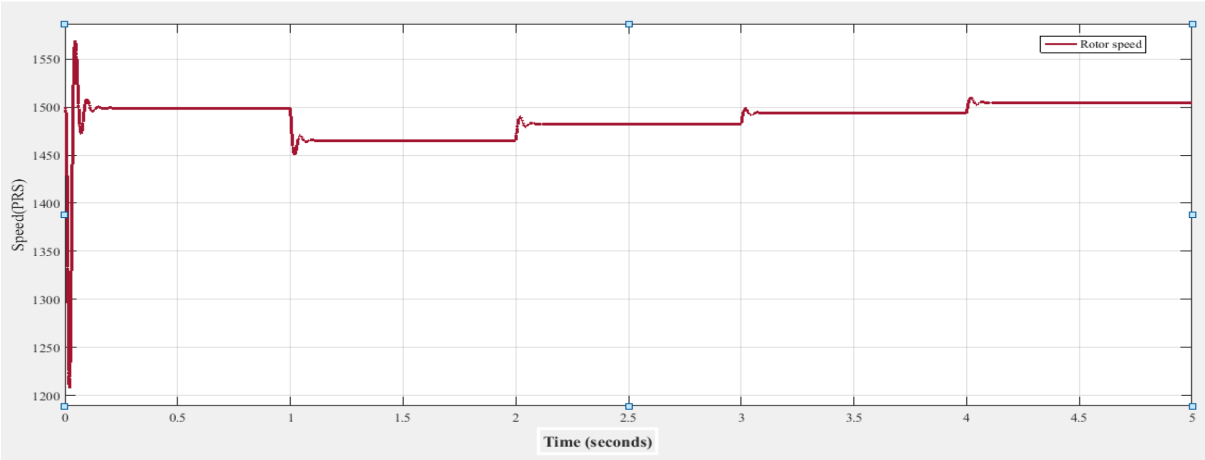

Fig. 11: Rotor speed at 15kW conventional source

The rotor speed of the induction motor rapidly stabilized when power was sourced from the conventional source, However, when the PV system was utilized to supply power to the induction motor, the rotor speed exhibited fluctuations. This observation indicates that the conventional power source, which has an equivalent capacity to the PV system, performs better than the PV system. Therefore, innovative strategies are required to address the oscillations that occur when the PV system is used to operate the asynchronous motor.

Shown in figs. 12 and 14 is the electromagnetic torque of the induction motor when powered from both sources to supply the 15kW inductive load.

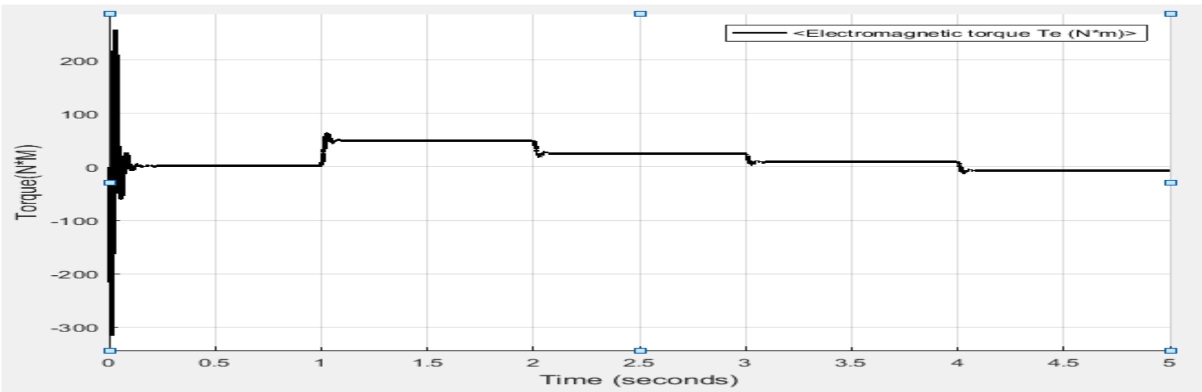

Fig. 12: Electromagnetic torque of the rotor at 15kW from conventional source.

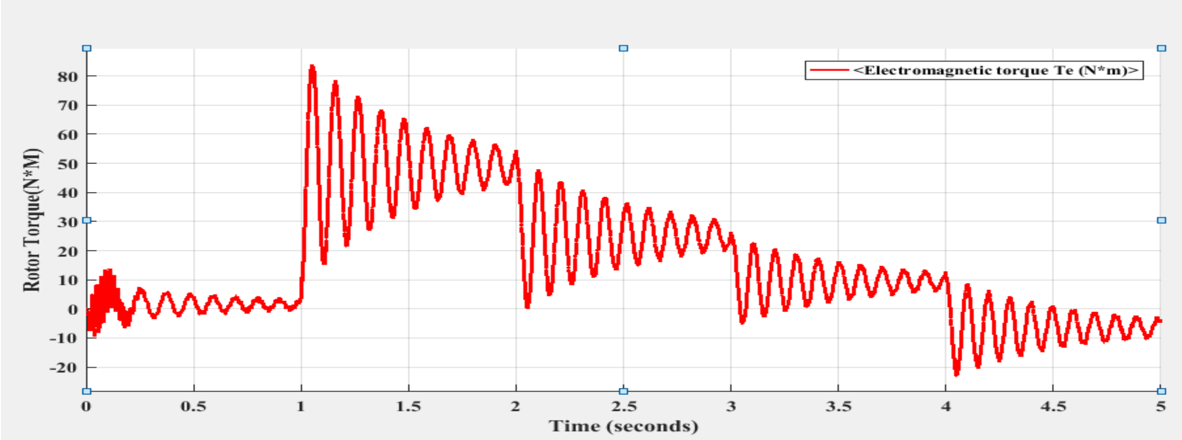

Fig. 14: Electromagnetic torque of the rotor rated at 15kW from PV system

The fluctuation in the rotor torque is significant, when the inductive load was supplied by the PV system, since it is not a redundant source like the conventional source. The toggle effect was significantly reduced when the conventional source of same capacity was deployed.

Shown in figs. 16 and 17 is the rotor current waveform from the induction motor rated at 15kW when supplied from both sources (conventional and PV system) as follows:

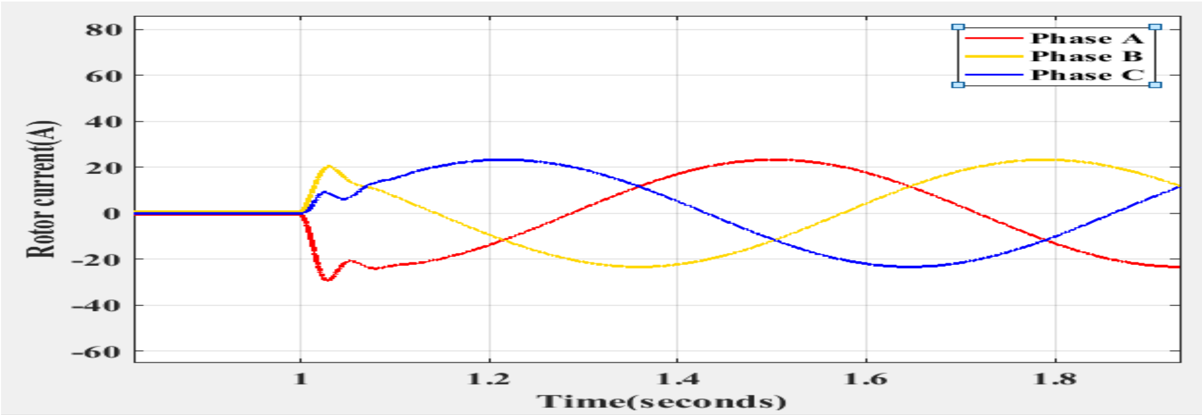

Fig. 16: Three-phase rotor current at 15kW from conventional source

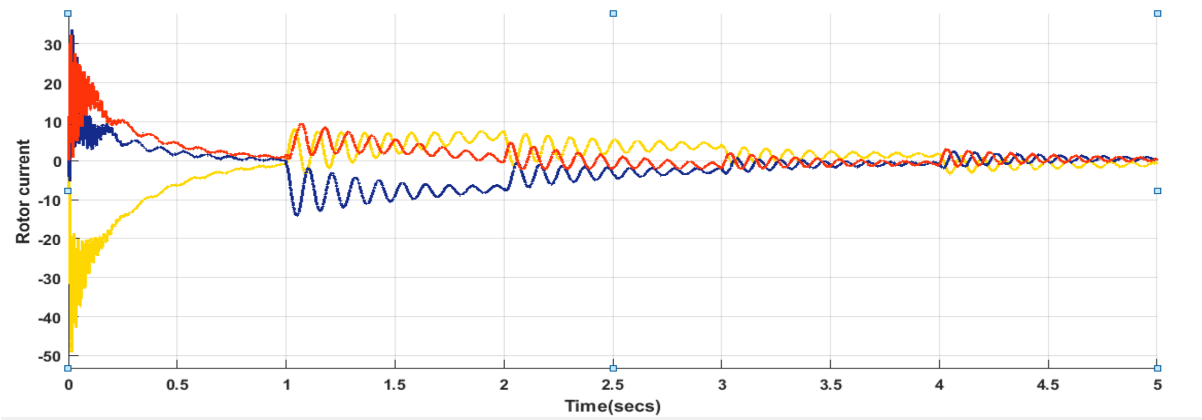

Fig. 17: Three-phase rotor current rated at 15kW from PV system

The rotor current signal waveform when powered from the PV system toggles frequently and also took a longer time to establish the required starting current for establishment of electromagnetic flux in the induction motor. whereas the conventional source been a redundant source quickly establishes the flux and stabilizes when subjected to interment loading conditions.

The current needed from the PV system to establish the electromagnetic flux greatly reduced, this showed a significant improvement in the PV system performance.

IV. CONCLUSION

The comparison between the performance of inductive loads powered by a PV system and a conventional electric power source revealed significant reduction in harmonics, efficiency, and stability in the asynchronous machine output when supplied from the conventional source, it emphasizes on the need for adoption of advanced strategies to mitigate low-frequency generation during DC to AC conversion. To enhance PV system efficiency, advanced measures for reducing low-frequency generation and increasing solar panel power rating and battery capacity should be carefully considered, especially for extended usage during adverse weather conditions.

V. RECOMMENDATIONS

It is therefore beneficial to deploy PV system for powering inductive loads, especially asynchronous machines due to their wide applications in various industries. To optimize their performance, it is essential to implement advanced control strategies, high-quality inverters and converters to ensure that a pure sinewave is obtained as well as to maintain a balance three phase system. Additionally, increasing the PV panels power rating beyond the load capacity, exploring advanced control systems, and conducting furthers research on diverse inductive loads and strategies to eliminate harmonics will enhance PV system efficiency, lead to substantial cost savings, and mitigate environmental impacts associated with greenhouse gas emission from combustion engines.

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