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Power Generation of Pure Sine Wave in Batteryless Solar System using Advanced Control

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Abstract- **A novel technique for conversion of DC power to AC power is introduced using solar powered sine wave generation system is presented. DC power extracted from solar system is made utilitarian for driving the BLDC (brushless DC) motor with constant speed constraints. The back EMF signals of each phase of the BLDC motor facilitated the development of technique for the sine wave generation from solar system without battery backup. This motor is coupled with AC generator, which yields the AC power on demand. The constant speed constraint is indispensable for fixed electrical frequency at the output of generator. A new control technique is rendered for reference tracking speed control of BLDC motor using Lyapunov theory by changing switching frequency, and also maintaining the voltage level at the output of converter driving BLDC by regulating the switching frequency of the zeta converter. The proposed methodology for generation of AC power from solar power system is also tested on prototype. The comparison of conventional technique for generation of sine wave power and proposed scheme is mentioned at later section of this paper for describing the efficacy of newly presented scheme.**

Index Terms-- **Zeta converter, BLDC motor, Solar powered sine wave generation (SPSWG), Voltage source inverter (VSI), Lyapunov Function, Sliding mode control (SMC).**

I. INTRODUCTION

Energy resources available to mankind are dwindling day by day, soon the scarcity of energy resources will imbalance its demand and supply system [1]. Energy resources available to mankind are dwindling day by day, soon the scarcity of energy resources will imbalance its demand and supply system [1]. This urged the scientists to invent new technologies to use renewable sources most efficiently. Energy extracts from solar is the most efficient way of renewable energy [2] and is being explored by researchers since last two decades. The solar photo voltaic (SPV) panels are used to get electrical energy from sunlight.

The output of SPV panels is in the form of DC voltage. The solar power system generally is composed of photovoltaic panels, charge controller, battery bank and an inverter to produce an AC output [3]. The two main components battery bank and inverter remained the integral part of solar power system. The battery bank used in solar system serves as a backup in the absence of solar power availability and also it endeavors to keep the DC voltage constant at the input of the inverter [4]. In the absence of battery bank, voltage at the input of the inverter may fluctuate excessively which may result in increased harmonics at the output of inverter. So, the absence of battery bank reduces the efficiency of sine wave inverters drastically [5]. Literature review establishes the presence of three types of inverters on the basis of output that is square, modified, pure sine wave inverters [6]. Square wave inverters and the modified sine wave inverters are likewise with a distinction that modified sine wave inverters has more levels in one complete wave. The main problem with modified sine wave inverter is that it cuts the working efficiency of driven devices because of harmonics and ripples in its output [7]. Especially the motors develop a hissing or buzzing sound. This badly shortens the life of equipment. Efforts are continuously in progress to develop some techniques to get rid of these harmonic distortions by generating harmonics free pure sine waves from DC supply. For the purpose of increasing efficiency as well as the life of equipment such as motors, electronic devices, researchers are in continuous effort to develop some harmonic free DC to AC conversion systems.

Also some new technologies have been emerged in the recent past [8] for conversion of DC power to AC power. Except the traditional buck-boost converters, zeta converter [9] and Cuk converter [10] are also proposed in the literature. These converters are also designed with maximum power point tracking feature [11]. However, the problem with these converters is still that their output is not pure sine wave. The zeta converter is elaborated in solar power-based applications in [12-14]. Additionally, a scheme to drive a motor pump by BLDC motor utilizing zeta converter which is initially fed with solar power has been rendered in [9]. By combining motor drives, DC/DC converters and the zeta converter in connotation with a BLDC motor is presented effectively in [9]. The marvelous characteristics of long life reliability and high power efficiency BLDC motor and the zeta converters are amalgamated to produce pure sine wave output of electrical power. The advantages of both BLDC motor and zeta converter devotes to give a solar photovoltaic array fed electrical power system having sinusoidal voltage at the output and operating effectively under variant atmospheric conditions. Because of High efficiency, low noise and high inertial ratio of BLDC motor doesn’t need any maintenance [15-16]. A zeta converter claims better status over the traditional Cuk converter and buck/boost converters when engaged in solar power system driven appliances [17]. The zeta converter produces continuous output current different to a conventional buck/boost converter [10]. The zeta converter performs as uniform buck/boost converter contrasting a non-uniform buck/boost converter and Cuk converter. These advantages of the zeta converter are encouraging for desired solar power system with pure sine wave at its output.

A water pumping system energized by solar power fed BLDC motor was proposed in [18]. Zeta converter was an integral part of that system to withdraw the power from solar panels. The presence of only one MOSFET switch, zeta converter shows better efficiency. The continuous conduction mode of zeta converter lessens the stress on its power components. Moreover, the additional power saving because of the switching power loss of voltage source inverter (VSI) is decreased [18].

In this paper we have developed a solar power sine wave generation (SPSWG) system by utilizing the BLDC motor and zeta converter to drive the AC generator. BLDC motor desired speed can be achieved by controlling the switching frequency of zeta converter and VSI. The intent of our research is to establish an effective methodology to get harmonics free pure sine wave from DC power source, such as solar power systems. The proposed technique is simulated, tested and verified by means of prototype.

Problem statement: To produce the harmonic free, pure sine wave in solar power system without battery bank is our problem. Moreover, the proposed system is compatible to grid connectivity.

II. DESIGN ARCHITECTURE OF THE SOLAR POWER SINE WAVE GENERATION (SPSWG) SYSTEM

A. *Architecture of the SPSWG System*

The theme of our proposed solution to get the inverted power in desired sinusoidal form can be apprehended by the following Fig. 1.

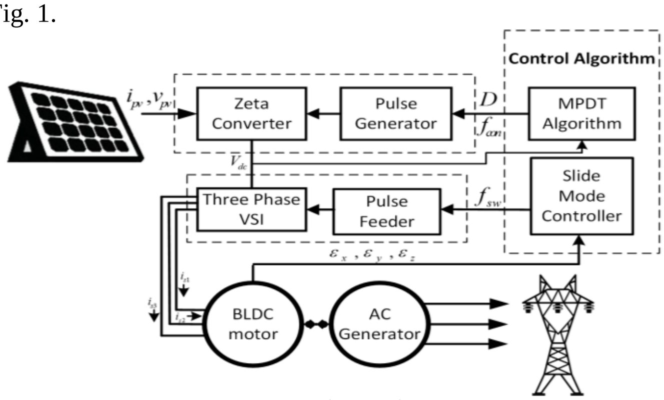

FIGURE 1: Proposed architecture Of SPV fed BLDC motor to drive AC generator.

Along with the main objective of producing sinusoidal output, demanded electric power extraction is also pursued with a pre-requisite that the demanded power is less than the available solar power. By means of zeta converter, this extraction made possible. Zeta converter groups some useful features relative to the conventional buck-boost converters that are buck/boost converters [19, 20]. The zeta converter can buck or boost the voltage. The speed control algorithm of brushless DC motor is established through a voltage control at the input of VSI along with the alteration of switching frequency f_{sw} of pulse feeder unit for driving the BLDC motor according to specific control proposed in later section.

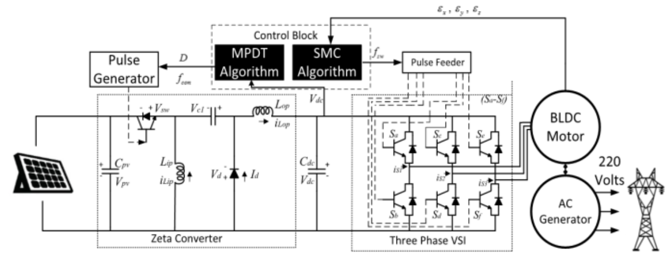

FIGURE 2: Illustration of Proposed Scheme.

By means of zeta converter, the smooth starting of BLDC motor can be achieved [16]. This property ensures the effective operation of a system because of the smooth starting of BLDC motor is different from the starting of BLDC motor with a boost converter which doesn't ensures the smooth starting of BLDC motor. By these unique features, zeta converter tracks the required power to run the BLDC motor at desired speed. BLDC motor speed is controlled by a feedback control scheme. The back EMF of any of the three phases is fed back to the electronic commutation unit to sense the speed of BLDC motor. This unit performs switching of the VSI unit, so that the BLDC motor speed is maneuvered by changing the applied voltage to the BLDC motor. An alternator coupled with this BLDC motor generates the AC power from SPSWG system. Smooth and controlled speed of BLDC motor is coupled with AC generator to drive the AC generator. The fixed speed of AC generator will ensure the generation of pure sine wave voltage at its output.

B. *Features Persuaded for the Proposed System*

The SPV fed BLDC motor drive is designed in such a way that smooth and controlled speed of BLDC motor coupled with the AC generator is made possible. The controlled rated speed of AC generator will ensure the generation of pure sine wave voltage with 50 Hz frequency. Our proposed system's schematics demonstrated in Fig. 2, in which SPV array, zeta converter and three phase VSI system are coupled through DC link capacitor.

III. MODELING OF BRUSH LESS DC MOTOR

Three phase windings on the stator of BLDC motor constitute the main circuitry to produce magnetic flux of stator while the rotor magnets are usually permanent magnets which interact with the rotor magnetic field, in this way resulting torque will rotate the BLDC motor's rotor.

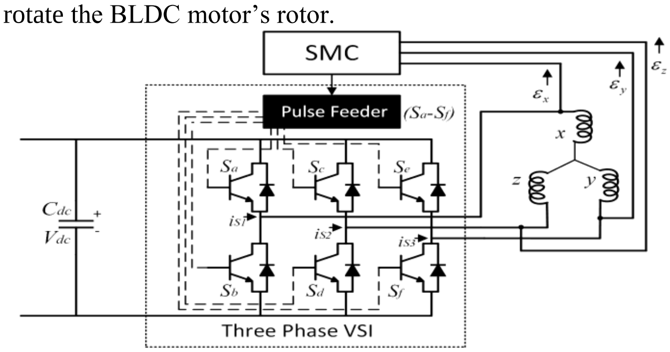

FIGURE 3: Schematics of BLDC Motor and VSI

Figure 3 explains the basic architecture of the inverter and BLDC motor that results in a system which produces a uniform speed torque characteristics [21, 22]same as in traditional DC motor. The BLDC motor is also mechanically coupled with the AC generator. The corresponding circuit of any one phase of the BLDC motor is illustrated in Fig. 4. Two phases of stator windings carry currents and establishes the torque at any instant.

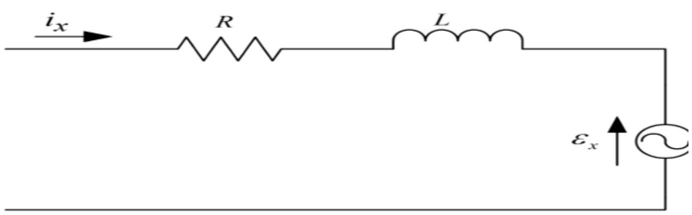

FIGURE 4: Equivalent Circuit of the phase x [23].

For simpler representation, BLDC motor analysis is based on the succeeding assumptions [24, 25].

Assumptions:

Resistances of the all windings of stator are same; similarly values of mutual inductance and self-inductance of stator windings are constant. Likewise the BLDC motor is energized below saturation and electronic components in the inverter exhibit ideal behavior.

The stator windings characteristics can be depicted by mathematical representation as shown in (4).

$$V_x = Ri_x + L\frac{di_x}{dt} + \varepsilon_x \tag{1}$$

$$V_y = Ri_y + L\frac{di_y}{dt} + \varepsilon_y \tag{2}$$

$$V_z = Ri_z + L\frac{di_z}{dt} + \varepsilon_z \tag{3}$$

Here in these equations $L = L_x = L_y = L_z$ are the self-inductances of each phase, R is the resistance of each phase, Here ε_x, ε_y, ε_z are back EMFs of phases x , y , z respectively.

As, the value of these back EMFs depends upon the amount of rate of cutting the magnetic flux, so the back EMF of one phase that is phase x is manifested by means of (4).

$$\varepsilon_x(t) = M_x\omega_x(t) \tag{4}$$

The back EMFs of all the phases x , y , z in matrix representation are described as follows:

$$\begin{bmatrix} \varepsilon_x(t) \\ \varepsilon_y(t) \\ \varepsilon_z(t) \end{bmatrix} = \begin{bmatrix} M_x\omega_x(t) \\ M_y\omega_y(t) \\ M_z\omega_z(t) \end{bmatrix} \tag{5}$$

According to current conduction states as shown in Tab. I, the operation of three phases VSI can be allocated into six modes.

TABLE I: PATTERN OF COMMUTATION FOR DIFFERENT POSITIONS OF ROTOR SHAFT [25]

Rotor shaft position	Inputs sequence to corresponding switches of inverter circuitry					
	S_a	S_b	S_c	S_d	S_e	S_f
NA	✗	✗	✗	✗	✗	✗
0-60	✓	✗	✗	✓	✗	✗
60-120	✓	✗	✗	✗	✗	✓
120-180	✗	✗	✓	✗	✗	✓
180-240	✗	✓	✓	✗	✗	✗
240-300	✗	✓	✗	✗	✓	✗
300-360	✗	✗	✗	✓	✓	✗
NA	✗	✗	✗	✗	✗	✗

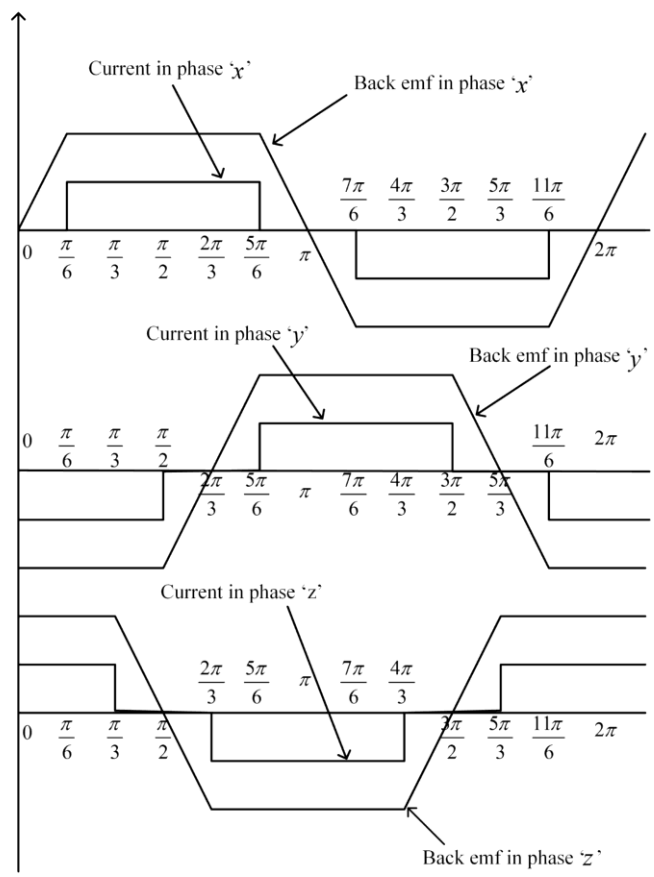

FIGURE 5: The trapezoidal back EMF on each phase of the stator windings [26, 27].

Active switching modes for three phase VSI operation and the corresponding back EMF waveforms and also flowing current representing waveform are illustrated in Fig. 5. Feedback system is shown in Fig. 6.

After having the above available information, we can proceed further with a claim that, in BLDC motor, all the phase coils are tightly mounted with each other, that is why mechanical speed or ω remains same i.e. $\omega_x = \omega_y = \omega_z = \omega$. This fact inculcates the representation of (5) as follows:

$$E(t) = M\omega(t), \tag{6}$$

where $E(t) = \begin{bmatrix} \varepsilon_x(t) \\ \varepsilon_y(t) \\ \varepsilon_z(t) \end{bmatrix}$, $M = \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix}$.

M_x, M_y, M_z are the mutual inductances of all the mentioned phases.

IV. Sensorless Controller Design For Fixed Speed BLDC Motor

The sole objective of tracking the reference speed by BLDC motor all the time is developed by controlling the two switching frequencies that is f_{con} and f_{sw} simultaneously

A. *Converter switching frequency f_{con} control*

Duty cycle of zeta converter can be calculated by means of (7) [9].

$$D = V_{dc}(V_{dc} + V_{pv})^{-1} \tag{7}$$

where V_{dc} represents the DC voltage across the filtering capacitor at the output of the zeta converter. V_{dc} is the voltage at the input of the BLDC motor to produce the torque to drive the alternator for matching the load demand. It is important to mention that if BLDC draws more current to produce the required torque then V_{dc} decreases and this is again boosted by increasing the switching frequency of zeta converter switch that is f_{con}, according to (8) [9].

$$f_{con} = \frac{DV_{dc}}{L_{ip}\Delta I_{L_{ip}}} \tag{8}$$

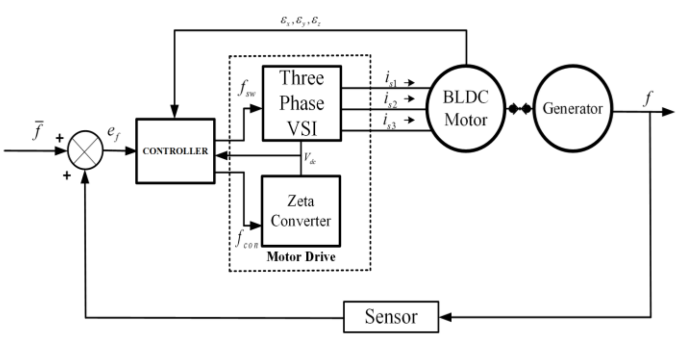

FIGURE 6: Feedback System of Desired Approach.

B. *VSI switching frequency f_{sw} control*

In our proposed methodology for speed control, back EMF induced in each coil is directly fed to the control unit after scaling it to an appropriate level. Back EMF induced in all the phases of stator winding i.e. ε_x, ε_y and ε_z depends on time rate of change of flux linkded between rotor permanent magnet and stator winding. For controlled motor speed, the maximum amplitude of the back EMF of phase 'x' is compared with the reference value. If the back EMF is greater or equal to the desired reference value of speed signal, the controller comes into action and generates the control signal to bring the rotation speed of the BLDC motor to the reference value. This control signal is engineered in the following way.

Assumption 2: Assume the reference speed is $\bar{\omega}(t)$ and the maximum value of back EMF at this reference speed for each of the x, y, z phase is $\bar{\varepsilon}$.

Defining the error between desired speed and the speed of BLDC motor as follows:

$$\left.\begin{aligned} e_{\omega x}(t) &= \bar{\omega} - \omega_x(t) \\ e_{\omega y}(t) &= \bar{\omega} - \omega_y(t) \\ e_{\omega z}(t) &= \bar{\omega} - \omega_z(t) \end{aligned}\right\}, \tag{9}$$

and also, back EMF errors,

$$\left.\begin{aligned} e_x(t) &= \bar{\varepsilon} - \varepsilon_x(t) \\ e_y(t) &= \bar{\varepsilon} - \varepsilon_y(t) \\ e_z(t) &= \bar{\varepsilon} - \varepsilon_z(t) \end{aligned}\right\}. \tag{10}$$

We can conclude from (6), (9) and (10) that $e_i(t) = M_i e_\omega(t)$ where $e_i(t) = \bar{\varepsilon} - \varepsilon_i(t)$ with $i = x, y, z$ .By assuming $M_x = M_y = M_z = M$, as mentioned above that i represents for all three phases x, y, z.

$$e_i(t) = M_i e_{\omega i}(t) \tag{11}$$

As e_i represents error for all three phases, which shows the similar behavior. We can take back EMF error of any of the three phases for our control purpose. Let us we take back EMF error of the phase x in our control scheme.

$$e_x(t) = M_x[\bar{\omega} - \omega(t)] \tag{12}$$

In case of alternators, the electrical frequency of the output voltage is directly linked with the mechanical speed, so we can write,

$$\omega = Hf_e \tag{13}$$

Here constant H depends upon the number of poles of alternator. This alternator and the BLDC motor are mechanically coupled. Also, it is well known fact for any BLDC motor, that under condition of constant DC input voltage to the VSI, the BLDC motor's speed depends upon the switching frequency of the VSI [28],

$$\omega = G * f_{sw} . \tag{14}$$

Where f_{sw}= Switching frequency, G= is constant, its value depends upon no. of poles of BLDC motor and other physical parameters of BLDC motor. From (13) and (14),

$$f_{sw} = N\, f_e , \tag{15}$$

here $N = H / G$, by utilitarian of (14) into (12), we get (16),

$$e(t) = M[\bar{\omega} - G * f_{sw}] . \tag{16}$$

For the asymptotic convergence of the error $e(t)$, by means of proposed controlling scheme using the switching frequency f_{sw}, to maneuver the speed of rotor of BLDC motor equal to the reference value, sliding mode control (SMC) based scheme is rendered. The sliding surface is capable of keeping the speed variation of BLDC motor because of bounded variations of load, coupled with the generator. Sliding surface for controlling the speed of BLDC motor is proposed as follows:

$$S(\dot{f}_{sw}) = \begin{cases} \dot{f}_{sw} = +k & \dfrac{d\,e(t)}{d\,t} > 0, \\ 0 & \dfrac{d\,e(t)}{d\,t} = 0, \\ \dot{f}_{sw} = -k & \dfrac{d\,e(t)}{d\,t} < 0. \end{cases} \tag{17}$$

Here, k is a constant value, for changing the response time, that is, the time required by the BLDC to reach the reference speed. The value of k is varied accordingly. The value k can be positive, negative or zero. It is important to mention that value of k is utilized to alter the rate of asymptotic convergence of error (8).

C. Theorem:

A sufficient condition for the asymptotic convergence of speed error (8) with a pre-requisite that more solar power is available than the demanded power a constraint for scalar $J > 0$ along with is that if $\bar{\omega}/(2KG) > f_{sw}$ increase the switching frequency and vice versa.

Proof:
Using Lyapunov theory [29], We can assume an energy function as follows:

$$V(t) = Je(t)e^T(t) \tag{18}$$

The time rate of change of Lyapunov's energy function is

$$\dot{V}(t) = 2\,Je(t)\,\dot{e}(t)$$

From (12), we can write, (14)

$$\dot{V}(t) = 2\,J\,e(t)\frac{d}{d\,t}[M(\bar{\omega} - G * f_{sw})],$$

$$\dot{V}(t) = 2\,J\,e(t) G * \dot{f}_{sw} ,$$

$$\dot{V}(t) = 2\,J[M(\bar{\omega} - G * f_{sw})]G * \dot{f}_{sw} ,$$

(15)

$$\dot{V}(t) = 2\,J\,M(\bar{\omega}\, G\, \dot{f}_{sw} - 2\,J\,G^2 f_{sw}\, \dot{f}_{sw}) . \tag{19}$$

For the Lyapunov stability condition, the time rate of change of energy function should be negative, that is

$$\dot{V}(t) < 0 ,$$

$$2\,J\,M(\bar{\omega} G\, \dot{f}_{sw} - 2\,K\,G^2 f_{sw}\, \dot{f}_{sw}) < 0 ,$$

$$2\,J\,M\,G(\bar{\omega}\, \dot{f}_{sw} - 2\,J\,G\, f_{sw}\, \dot{f}_{sw}) < 0 ,$$

where is always $2\,J\,M\,G > 0$, so

$$(\bar{\omega} - 2\,J\,G\, f_{sw})\, \dot{f}_{sw} < 0 .$$

From above, one can conclude the following two cases.

Case 1:
If $\dfrac{\bar{\omega}}{2\,J\,G} > f_{sw}$ then change the switching frequency positively.

Case2:
If $\dfrac{\bar{\omega}}{2\,J\,G} < f_{sw}$ then change the switching frequency negatively.

This completes the proof.

V. Design Calculations For Implemented System

The proposed scheme is implemented on scaled system (prototype) in which the rated output of AC generator is $150\,VA$ Power rating of solar panels is kept more than the maximum rated output power rating of the alternator. Power rating of BLDC motor with capability to run at maximum speed of 3300 rpm is $200\,W$. The mechanical torque developed in this BLDC motor shaft is sufficient to run the alternator driving its rated load. That is, it can drive the AC generator of 6 poles with the constant speed of $3000\,rpm$ to produce desired 220 AC volts with 50 Hz frequency. A noticeable amount of electrical power available through photo voltaic panels is lost in the power converters because of various power losses in the converter circuitry. For sensible agreement between the losses and output an appropriate size of solar photo voltaic array with appropriate power rating which is mentioned as a pre-requisite in Theorem for the realizing the operation of our system is selected. So, peak power capacity of SPV array is $250\,W$, which is larger than the power offered by the BLDC motor driving circuitry, is chosen and its parameters are also designed according to required condition.

A. Solar panel

The specifications of selected solar module have been mentioned in the Tab. II [29].

TABLE II: SPECIFICATIONS OF SONNENSTROMFABRIK 250P60

Maximum Power ($P_{\max}$)	250
Voltage at Open Circuit($V_{o.c}$)	37.62
Current at Short Circuit ($I_{o.c}$)	8.91
Voltage at MPD (V_{mpd})	29.73
Current at MPD (I_{mpd})	8.41
Panel Efficiency	15.2%
Power Tolerance ($+ve$)	+3%
Power Tolerance ($-ve$)	-3%

All specifications of solar module is verified under standard test conditions. Voltage of Solar Photovoltaic array is $V_o = 24v$ and the current of Solar Photovoltaic array at maximum power demanded (MPD) can be calculated using $i(t).v(t) = P(t)$. The maximum power P_o required by BLDC motor to drive its load (generator) at reference speed of 3000 rpm . From this the value of I_o is taken as 10.4 A .

B. Zeta Converter:

Zeta converter which is DC to DC converter that regulates the unregulated input power supply [9]. All Components of zeta converter that is L_{ip} , L_{op} , C_1 are designed in such a way so that Zeta converter operates in CCM to decrease the stress on its components and devices. The values for L_{ip} , L_{op} and C_1 values are estimated as [8]. Hardware setup consists of a SPV solar switch which has been fed with the solar modules, BLDC motor of $200\,W$ having $3300\,rpm$ which is coupled with the AC generator of $150\,W$ having $3000\,rpm$, zeta converter as a DC/DC converter. Figure 7 shows the hardware of prototype of the proposed SPSWG System.

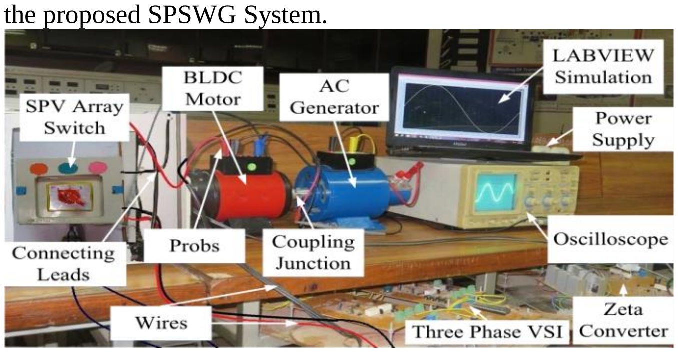

FIGURE 7: Hardware Demonstration of SPSWG

VI. COMPARISON BETWEEN CONVENTIONAL SOLAR POWER SYSTEM AND PROPOSED SYSYTEM

Efficiency of proposed system is far better than conventional solar power systems, in traditional systems; their structure consists of a SPV array panel which is being fed with the DC/DC converter (buck-boost) along with the DC battery which connects with the inverters for DC to AC conversion. Conventional solar power system (SPS) has been shown in Fig. 8. Literature, shows that the losses in a DC battery (75% efficiency, 25%losses) [30] is due to charging and discharging heat loss and due to corrosion affects etc. is a big concern and other power losses (eddy current loss, hysteresis loss) in a step up transformer (94% efficiency, 6% losses) [31] in an inverter makes it even less efficient because of more power dissipation. Conventional buck-boost converters (98% efficiency, 2% losses) having slow switching speed also causes the power loss in a solar power system. By keeping in view making proposed system more efficient all the factors cause power dissipation have been rejected in the desired system. Figure 9 shows the comparison of how proposed system is different from conventional SPV. Instead of DC battery proposed scheme used a DC link capacitor (99.5% efficiency, 0.5% losses) which can store charge and is more efficient than DC battery [32].

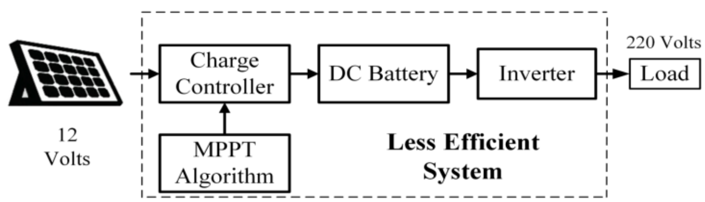

FIGURE 8: Conventional Solar Power System Scheme

zeta converter (98.2% efficiency, 1.8% losses) has been replaced with buck-boost converter due to its good switching speed [33], AC generator (96% efficiency, 4% losses) [34] gives the $220\,V$ AC voltage at output in pure sine wave satisfies the effective working of proposed system.

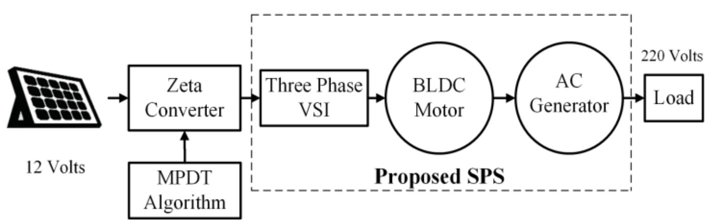

FIGURE 9: Proposed Solar Power System Scheme

VII. AC GENERATOR OUTPUT FREQUENCY

On increase of an electrical load of the AC generator in the prototype, the mechanical speed of rotation of the generator is decreased as can be witnessed in Fig. 10, which shows that load is applied after ‘2 sec’ time which results a decrease in generator speed of rotation below 3000 rpm which is also coupled with the BLDC motor. This decreased speed of generator causes a dip in graph. This actually causes the drop of electrical frequency at the output of the generator. To cater this problem, speed control of the BLDC motor is applied by controlling the duty cycle and switching frequency of converter and also controlling the switching frequency of voltage source inverter at the input of BLDC motor. So, the desired objective is to minimize this drop and maintains the output frequency of the SPSWG system that is 50 Hz.

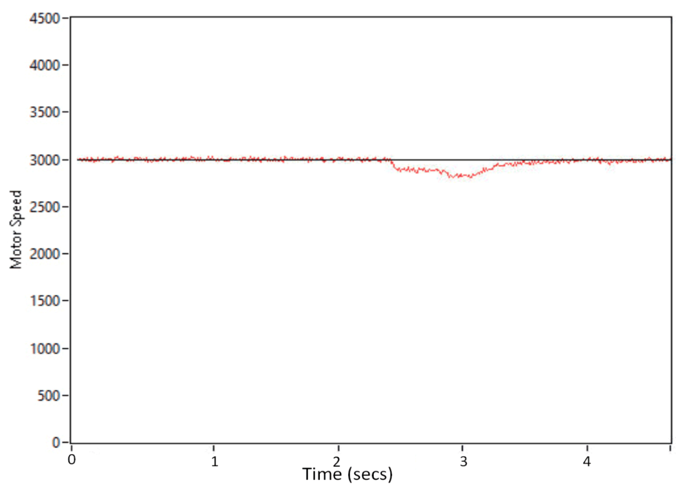

FIGURE 10: Rotational speed of BLDC coupled with AC Generator

VIII. CONCLUSION

A conversion of DC power to AC power is presented with a novel methodology of solar powered sine wave generation system. The BLDC motor is driven by a batteryless technique involving zeta converter and voltage source inverter at constant speed. The back EMF signals are utilized in the development of technique for the sine wave. The AC generator yields the AC power on demand. The constant electrical frequency at the output of generator is made possible with pure sine wave voltage at no load condition. A control scheme is rendered for reference tracking speed control of BLDC motor using Lyapunov theory. This control scheme maintains the speed of BLDC motor even at varying load conditions. The scheme is tested and verified by means of prototype. The comparative analysis between the conventional solar power generation systems and the proposed system is also presented.

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