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An improved PV system with auto-protection to inject active power into the power grid of marine ships

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Photovoltaic (PV) system is turning into an ideal secondary power source for marine ships because of the ability to trap nature's green energy. In this paper, a ship's power grid connected PV system is proposed. The proposed system will help to inject the active power into the ship's electric power grid together with a protection scheme, which will prevent the PV system and ship's power grid from different faulty conditions. The proposed system has facility to track the maximum power point (MPP) of PV array by means of hybrid MPPT method and flyback DC-DC converter. Space vector pulse width modulation (SVPWM) technique controlled 3-phase full-bridge VSI is used to convert DC bus voltage into useful 3-phase AC output in order to feed the local load and transmit excess AC power into the ship's bus. Furthermore, an isolation transformer is used to provide galvanic isolation amid PV system and ship's power grid.

[**Keywords**: Duty cycle, EDS, Flyback converter, Local-load, MPPT, MPP, Photovoltaic SVPWM ship's bus]

Nomenclature:

V_{PV}	PV array's output voltage	MPP	Maximum Power Point
I_{PV}	PV array's output current	MPPT	Maximum Power Point Tracking
P_{PV}	PV array's output power	DC	Direct Current
D	Duty cycle of flyback converter	AC	Alternating Current
V_{in}	Input voltage to the chopper	THD	Total Harmonics Distortion
V_{out}	Output voltage of chopper	VSI	Voltage Source Inverter
V_{out}'	Output voltage of chopper seen by the primary side	CSI	Current Source Inverter
N_p	No. of turns in primary side of transformer	PWM	Pulse Width Modulation
N_s	No. of turns in secondary side of transformer	SPWM	Sinusoidal Pulse Width Modulation
e	Error signal	SVPWM	Space Vector Pulse Width Modulation
c	Photo-Voltaic	RMS	Root Mean Square

Introduction

Without any uncertainty, the most recent decade was the terrific lifespan for the photovoltaic systems. The enormous number of technological advances on the research parts of photovoltaic (PV) panels, micro-grids, and power electronics has extended the usage of PV panels into frequent applications. Furthermore, fuel cell generators, wind power systems, PV systems, batteries, and other renewable energy generation structures can work collectively to establish reliable micro-grids[1-4]. Nonetheless, the utmost common PV applications are the power grid-tied systems, where lone PV panels or bulky scale PV plants supply secondary electric power to the power grid[4-6]. Although their stretched uses in continental applications, the manifestation of PV systems in recent marine technology remains narrow, mostly working as supplying units for navigation units, small lighthouses, and battery chargers for the minor sailing ships[7]. The growing transportation expenditures because of the fuel prices, the growing limitations of NO$_x$, nitric oxides and CO$_2$ emission as a result of new environment protection policies, and mostly the requirement for further environment friendly shipping were the motivation that forced the naval firms to reconsider the organized use of PV systems on bulky vessels[8,9]. The photovoltaic systems can without a doubt be a surely cost-effective answer for ships. PV systems can turn as ideal secondary power sources, liberated from the vessel's traditional electromechanical systems for the following reasons[10].

They harvest electric power with lacking need carrying liquid fuel or transport gas.

They cause no gas emissions or noise.

They have low maintenance cost.

They have very few or else no use of moving parts.

They are made up of a small number of parts, with stress-free installation and easy replacement in the circumstance of malfunction or getting old.

They have warranted performance for an acceptable lifespan, which is generally more than 80 % as that of a new system after 25 years of operation.

They can be positioned in unimportant exteriors with no everyday usage such as walls, roofs etc.

In this paper, an investigation is done to answers that, how the utmost widespread technologies of the continental PV systems can be realized for marine applications, and what qualifications must be achieved to design a PV system suitable for moderate or complete electrical marine vessels.

Materials and Methods

The proposed model of ship's bus connected PV system is an improved system to feed the local load and transmit excess solar energy into the electricity distribution system of ship. To simulate the model MATLAB R2017a Simulink software is used. The block diagram of the proposed system is shown in Figure 1.

Components of bus-tied PV system

Following are the components of ship's bus connected PV system

1. PV array
2. Maximum Power Point Tracking System
3. DC/DC converter
4. AC-AC converter
5. Inverter control scheme
6. Filter
7. Isolation transformer
8. Protection circuit
9. Circuit breaker
10. Electricity distribution system of ship

Ship's electricity distribution system

A marine ship can be well-thought-out as a mobile power plant. Four distinct areas can be well-known in the electric system of a classical ship are the generators, the main propulsion engine, the loads, and the main distribution bus[27].

Agreeing to the studies, the output voltages of the diesel and main generators fluctuates. Usual values of output voltage magnitudes are 13.8 kV, 6.6 kV, 6 kV, 4.16 kV, 3.3 kV and 3 kV; whereas, frequency is 50 Hz to 60 Hz[10-12]. Electrical load is the end part of the ship's (EDS) electricity distribution system. There are various types of connected loads, however the utmost mutual are the DC 400 V and 24 V, the single-phase AC at 230 V, 50 Hz and the 3-phase AC at 400 V, 50 Hz loads.

PV array

Photovoltaic panels and array transform the solar energy into DC electricity. A photovoltaic array is a system made up of several solar panels electrically held together to form a considerably larger PV installation called an array and overall, the electricity produced by the solar panels is directly proportional to the surface area of PV panels[13]. For the simulation, a PV array of 10 series connected modules per string in 5 parallel strings. This PV array is having 700 V peak DC voltage in case of open circuit, 30 A peak current in case of short circuit and produces maximum power up to 18 kW. The equivalent circuit diagram of PV cell has already been reported[13] in literature and output PV current is given in equation 1.

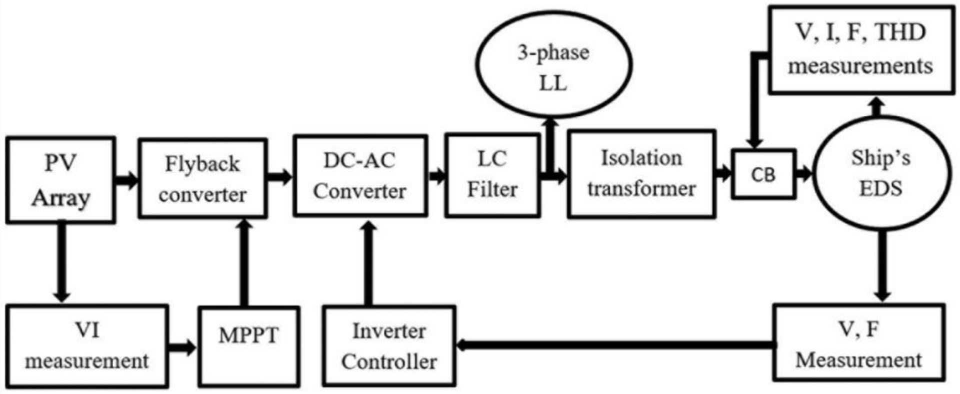

Fig. 1 — Block diagram of bus connected PV system for marine ships

$$I = I_L - I_o\left(e^{\frac{q(V-IR_S)}{AKT}} - 1\right) - \frac{V-IR_S}{R_{SH}} \qquad \ldots (1)$$

where, ‘V’ and ‘I’ stands for solar cell’s output voltage and current respectively, ‘I'_0 represents the dark saturation current, ‘q’ represents the charge of an electron, ‘A’ stand for diode quality factor, also identified as ideality factor, ‘k’ and ‘T’ symbolizes the Boltzmann constant and absolute temperature respectively, $'R'_{SH}$ and $'R'_S$ symbolizes the shunt and series resistances of the solar cell. For an ideal circumstance $'R'_{SH}$ would be infinite and $'R'_S$ would be zero.

Irradiance and temperature effect

Two significant influences that have to be taken care of are the temperature and the irradiation. They intensely affect the output characteristics of solar cells. Accordingly, the MPP fluctuates throughout the day and this is the key motive because of which the MPP must be continuously tracked to make certain that the solar panels harvest maximum obtainable power[14]. The influence of the irradiance and temperature on the V-I (voltage-current) and V-P (voltage-power) characteristics of PV array used for simulation is illustrated in Figures S1 and S2, respectively. There is a direct proportion between short-circuit current and irradiance, and inverse proportion between open-circuit voltage and temperature.

Flyback converter

Flyback converter is a device used as a DC to DC converter and has galvanic isolation amid input and output. Furthermore, flyback converter is advantageous to work for different input voltage levels while maintaining desired output voltage by providing appropriate transformer’s turn ratio. The flyback converter stands a modified version of a buck-boost converter in which inductor is fragmented to be used as a transformer. The working of flyback transformer is different from typical transformer as the low voltage and high voltage windings of the flyback transformer do not carry current at the same time[15,28].

Flyback converter is used to set-up or step-down the voltage depending upon the ON and OFF time period of the switch S per cycle. The circuit diagram of a flyback converter has already been reported in literature[15,28]. Its operating principle is very similar to that of typical buck-boost converter.

The ratio of output voltage to the input voltage is shown in equation 2. The ratio of ON time period to the total time period of switch S for a cycle is represented by duty cycle (D) as given in equation 3.

$$\frac{V_o}{V_i} = \frac{-D}{1-D} \qquad \ldots (2)$$

$$D = \frac{T_{ON}}{T_{ON} + T_{OFF}} \qquad \ldots (3)$$

Where, ‘D’ is Duty cycle.

For the reason of some applied limitations, the flyback converter is rarely used for output more than few hundred watts. Single-switch topology is adapted in Flyback converters but high breakdown voltage requirement of transistor is the downside of this topology. The commonly available IGBT transistors have 1200 V rating but they are very sluggish for the result of a productive flyback converter. To have fast operation MOSFETs are used instead of IGBTs. But for high voltage rated MOSFETs ON-state resistance is high which result in too much ON-state power loss in high-power applications.

Taking care of these draw backs of simple flyback converters, new MOSFETs are emerging, which are known as Silicon Carbide (SiC) MOSFETs. SiC MOSFETs has usually 1200 V rating. The ON-state resistance of these converters is low (considerably lower than 1 Ω, generally about 1 Ω) and very high switching speed. These MOSFETs are very efficient for high power flyback converters. The product number C2M0025120D in the standard TO-247 package of Cree industries has a breakdown voltage around 1200 V having 0.025 Ω ON-state resistance and drain current at 100 °C is nearby 60 A. The ON/OFF switching time is around 50 ns[16].

Also, the switching frequency of these SiC MOSFETs can be increased beyond 100 kHz for high power outputs. This increased frequency result in the requirement of low valued output capacitors. The common belief is that the flyback transformers are big in size but with proper design and by means of the help of high switching frequency the size of flyback transformers can be decreased even for high power outputs, for example ETD4917 core, with top view dimensions of (48.5 +1.3, -0.9)×(16.7 ± 0.8) mm.

MPPT techniques

Maximum power point tracking (MPPT) technique stands an electronic circuit system. MPPT techniques are adapted to control the duty cycle of the DC/DC converters connected across PV array in order to trace the maximum power point of PV array. The maximum power point of PV array is not a constant value but it changes with the alteration in irradiance and temperature of incident sun light. The power at MPP escalate with the increase in irradiance level and decrease with the escalation in temperature level[17,18,27]. The commonly used and basic MPPT technique is perturb and observe maximum power point technique. Dynamic and steady-state performance of various MPPT techniques is compared in literature[19].

Perturb and observe

Perturb and observe is a simple and basic MPPT technique. It is used to trail the maximum power point of the solar panels by changing the duty cycle of the chopper. This tracked duty cycle will help to maintain or change the chopper's output voltage at which the PV array's output power is maximum[20]. The flow chart of perturb and observe has already been reported in literature[20].

Incremental conductance technique modified with integral regulator

Incremental conductance came into picture to overcome the limitation of perturb and observe MPPT technique and by observing P-V characteristics. This set of rules came into picture in 1993. Incremental conductance attempts to produce more energy and improve the tracking time of PV array in continuously changing irradiance and temperature levels[21.28]. MPP can be evaluated by means of the relation among $\frac{dI_{PV}}{dV_{PV}}$ and $-\frac{I_{PV}}{V_{PV}}$.

Maximum power point is attained as soon as

$$\frac{dP_{PV}}{dV_{PV}}=0 \quad \text{... (4)}$$

where, $P_{PV} = V_{PV} \times I_{PV}$

$$\frac{d(V_{PV} \times I_{PV})}{dV_{PV}} = I_{PV} + (V_{PV} \times \frac{dI_{PV}}{dV_{PV}}) \quad \text{... (5)}$$

$$I_{PV} + (V_{PV} \times \frac{dI_{PV}}{dV_{PV}}) = 0 \quad \text{... (6)}$$

$$\frac{dI_{PV}}{dV_{PV}} = -\frac{I_{PV}}{V_{PV}} \quad \text{... (7)}$$

MPP is obtained when $\frac{dP_{PV}}{dV_{PV}} = 0$ and $\frac{dI_{PV}}{dV_{PV}} = -\frac{I_{PV}}{V_{PV}}$,

If $\frac{dP_{PV}}{dV_{PV}} > 0$, then $V_{PV} < V_{MPP}$ ... (8)

If $\frac{dP_{PV}}{dV_{PV}} = 0$, then $V_{PV} = V_{MPP}$ ... (9)

If $\frac{dP_{PV}}{dV_{PV}} < 0$, then $V_{PV} > V_{MPP}$ ... (10)

In this method, the ratio of instantaneous current to instantaneous voltage (conductance) and ratio of rate of change of current to the rate of change of voltage are compared. The duty cycle of chopper is varied depending upon the slope of power against voltage characteristics curve of PV array.

If tracked MPP lies on right side of actual MPP such that dI/dV< -I/V, at that time the value PV voltage should be decreased and if tracked MPP lies on left side of actual MPP such that dI/dV> -I/V, at that time the value PV voltage should be increased to grasp actual MPP. The PV voltage can be changed by changing the duty cycle of DC/DC convert which is connected across PV array. If dV = 0, and dI = 0 the duty cycle should remain same as that of previous value. If dV = 0 and dI> 0 then duty cycle should be increased. If dV = 0 and dI< 0 then duty cycle should be decreased. The flow chart explaining incremental conductance has already reported in literature[21,28].

Integral regulator is used to minimize error which is shown in equation 11.

$$\text{Error} = \frac{dI_{PV}}{dV_{PV}} + \frac{I_{PV}}{V_{PV}} \quad \text{... (11)}$$

The output signal generated by integral regulator is equal to the correction in duty cycle. The block diagram of incremental conductance modified with integral regulator is presented in Figure 2.

SVPWM controlled Voltage Source Inverter

In Power-Electronics, inverter stands in category of converters that runs on DC either DC current or DC voltage source and converts it into AC current or AC voltage, respectively. It is the opposite of the

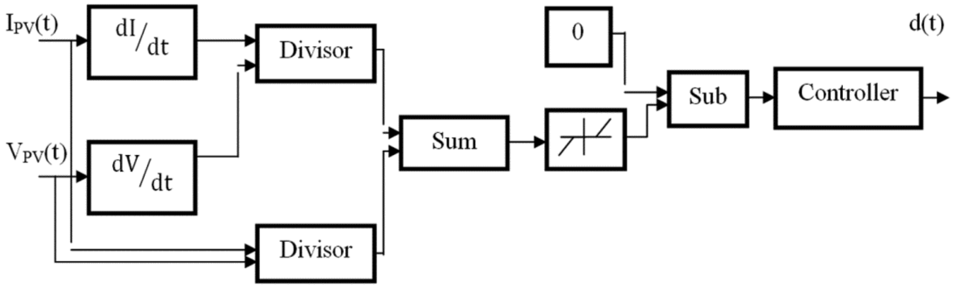

Fig. 2 — Incremental conductance modified with integral regulator

rectifiers. In voltage source inverter (VSI), the supply of inverter is a voltage source and in current source inverters (CSI) the supply of inverter is current source. The voltage waveform of ideal VSI does not depend on load coupled with it. Practically a VSI can be cast-off as both 1-phase and 3-phase configuration.

For a variable input voltage source, the output voltage of the VSI can be maintained constant by shifting the gain of the inverter. And gain can be varied using PWM technique. The typical circuit diagram of full bridge 3-phase VSI has already been reported in literature[22]. Switch S_1 to S_6 stands power switches which can be opened or closed by providing appropriate gate signal. This gate signal should be controlled by using inverter control scheme in a sequential manner. Space vector pulse width modulation is one of many inverter control schemes[22].

The eight likely combinations of gate signal given to three upper power switches are given in Table 1. The state of upper switches determines the state of lower switches of the respective leg. Corresponding to the gate signal vectors the line to neutral and line to line voltages are also given in Table 1.

With SVPWM control scheme inverter utilizes 15 % more input DC power than that of SPWN as compared in literature and cause lesser total harmonic distortions (THD) in the output[23]. The association among the gate signal vector $[abc]'$ and the phase voltage vector $[V_{an}V_{bn}V_{cn}]'$ is given in equation 12.

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad \ldots (12)$$

This control scheme is also helping to maintain the synchronization between PV inverter and ship's bus.

Protection circuit

There are some undesired fault conditions during the operation in electrical distribution system. Some of these faulty conditions are listed below:

1. Over voltage in the electricity distribution system of marine ship.
2 Under voltage in the electricity distribution system of marine ship.
2. Over current condition in the electricity distribution system of marine ship.
3. Formation of island, such that when there is power cut due to any fault in electricity distribution system of marine ship.
4. Any of the fault among symmetrical and unsymmetrical line faults.

The protection circuit of PV system should be able to sense these faults and give ON/OFF signal to the circuit breaker connected between PV system and ship's bus. During the faulty conditions, the circuit breaker should be able to isolate PV system and ship's bus to keep it out of the faulty electricity distribution system of the ship[3,24,25].

The electricity distribution of the ship is similar to a micro-power grid. According to the technical standards listed in the literature[26,28] to take care synchronization requirement and the safety requirements of the equipment connected to the ship's bus the protection circuit of PV system should be able to follow the conditions listed below:

1. The tolerable distinct harmonics level intends to be lesser than 3 % (individually, current and voltage harmonics) and Total Harmonics Distortion (THD) tolerable for both output current and output voltage intend to be lesser than 5 %.
2. If frequency grasps 50.5 Hz or more, and 47.5 Hz or below for at least 0.2 seconds, then the system should be able to provide a tripping signal.
3. At the point of interconnection, the system shall not be the reason for voltage fluctuation superior than ± 5 %.
4. If voltage ranges above 110 % or below 80 % for at least 0.2 seconds, then the system should be able to provide a tripping signal.

Table 1 — Gate signal vectors, line to line voltages and phase voltages

Voltage Vector	Gate signal Vectors			Line to line voltages			Line to neutral voltages		
	a	b	c	V_{ab}	V_{bc}	V_{ca}	V_{an}	V_{bn}	V_{cn}
V_7	1	1	1	0	0	0	0	0	0
V_6	1	0	1	1	-1	0	1/3	-2/3	1/3
V_5	0	0	1	0	-1	1	-1/3	-1/3	2/3
V_4	0	1	1	-1	0	1	-2/3	1/3	1/3
V_3	0	1	0	-1	1	0	-1/3	2/3	-1/3
V_2	1	1	0	0	1	-1	1/3	1/3	-2/3
V_1	1	0	0	1	0	-1	2/3	-1/3	-1/3
V_0	0	0	0	0	0	0	0	0	0

5. Inside the window of two seconds after the formation of an island, the protection circuit shall be able to spot the formation of island and terminate the energization of ship's bus.
6. The photovoltaic power systems, for the safety of inbuilt power converters, should have protection degree IP 54 for covered mounting and protection degree IP 65 for open-air mounting.

To protect the PV system and electrical distribution system of ship from these undesirable faulty conditions during the operation, a protection system is designed as presented in Figure S3. This protection circuit will detect the fault conditions and give signal to the circuit breaker connected in between PV system and power grid of ship. Furthermore, to provide galvanic isolation between PV inverter and ship's bus an isolation transformer is provided.

Results

Variable irradiance and temperature input to PV array are shown in Figure S4. Irradiance has been varied from 1000 W/m^2 to 400 W/m^2 and then again to 1000 W/m^2. Temperature has been varied from 25 °C to 40 °C. PV array's output is dependent on the input irradiance and temperature as explained in section irradiance and temperature effect. Corresponding to the input irradiance and temperature the output voltage, output current and output power are presented in Figure S5. PV output power at STC is 15.26 kW.

The waveforms of duty cycles of flyback converter controlled by incremental conductance with integral regulator and perturb & observe MPPT are presented in Figures S6 and S7, respectively. As shown in these figures, the proposed system that uses incremental conductance modified with integral regulator MPPT technique is having very few oscillations around actual MPP and less convergence time towards MPP as compared to perturb & observe MPPT. The output power of high power flyback converter continuously changing with the change in irradiance and temperature and is shown in Figure S8. Input DC power to the inverter at STC 13.5 kW, power at 400 W/m^2 & 25 °C is 5.8 kW and power at 400 W/m^2 & 50 °C is 12.42 kW.

The output signal of SVPWM for 0 to 3 seconds and 0.5 to 0.6 seconds is presented in Figures S9 and S10, respectively. This signal is such that it helps to control the inverter switches in such a manner so that the inverter and ship's power grid would synchronize. Frequency of this signal is 50 Hz.

Steady-state waveforms of DC bus voltage, output voltage and current feeding ship's bus are given in Figure S11. Instantaneous waveform of DC bus voltage, output voltage and current feeding ship's bus for 0.5 to 0.6 second are presented in Figure S12. The root mean square value of output voltage is 220 V and frequency is 50 Hz. As shown in these figures, voltage waveform is constant despite of variable input supply whereas current is varying with the change in input. These are the desired conditions.

Steady-state waveforms of inverter output voltage and output current are shown in Figure S13 and their instantaneous waveform for 0.5 to 0.6 seconds are presented in Figure 3. This current valued 20.8 A

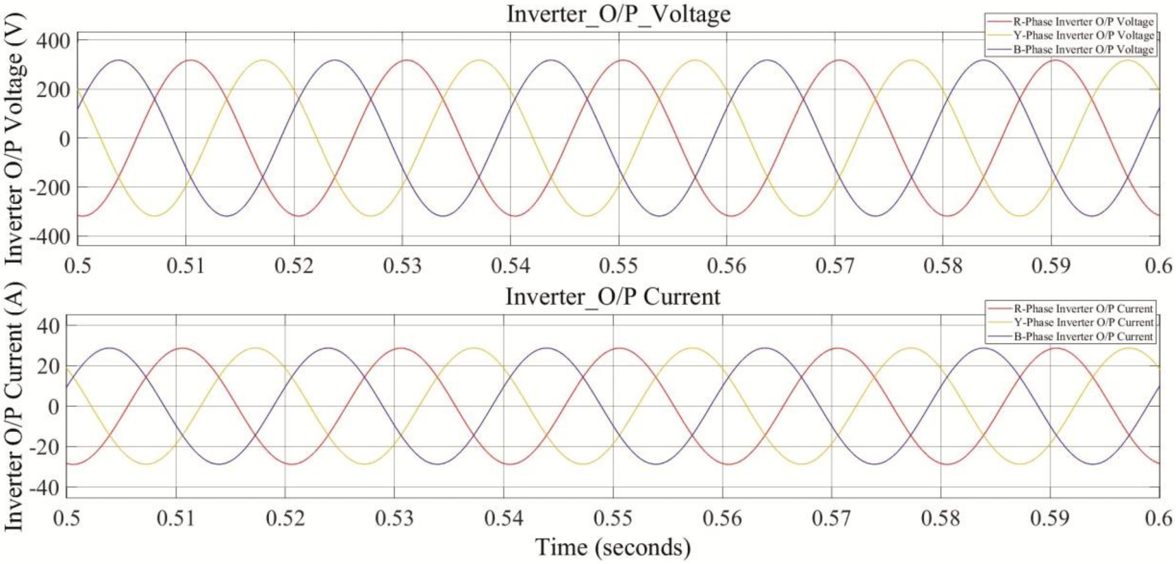

Fig. 3 — Inverter-side Instantaneous voltage and current output of inverter

(RMS) will further be distributed to feed the local load and power grid of ship. Voltage and current inputs to the local load are shown in Figure 4 and their instantaneous waveforms for 0.5 to 0.6 seconds are shown in Figure 5. RMS voltage value is 220 V and frequency is 50 Hz.

Active power, reactive power output of PV inverter, active power, reactive power injected into the grid is shown in Figure 6. These waveform shows that the maximum inverter output is contribution toward active power. At STC, active power delivered = 7.52 kVA.

During a 3-phase symmetrical fault in the power grid from 2.4 to 2.6 seconds of total simulation time, the low voltage and high current waveforms are presented in the Figure 7. This high value of current can damage the PV system and connected local load. The protection circuit is able to sense the fault and give the signal to circuit breaker. The signal generated by the circuit breaker is presented in Figure 8.

Inverter's steady-state output voltage and current at the point of interconnection with the power grid of ship is shown in Figure 9. In this figure, it can be observed that, during the time of fault the circuit breaker is able to disconnect PV system and ship's power grid within 0.1 seconds after the happening of fault. There is no any flow of current during fault between PV system and power grid of ship. Also, the

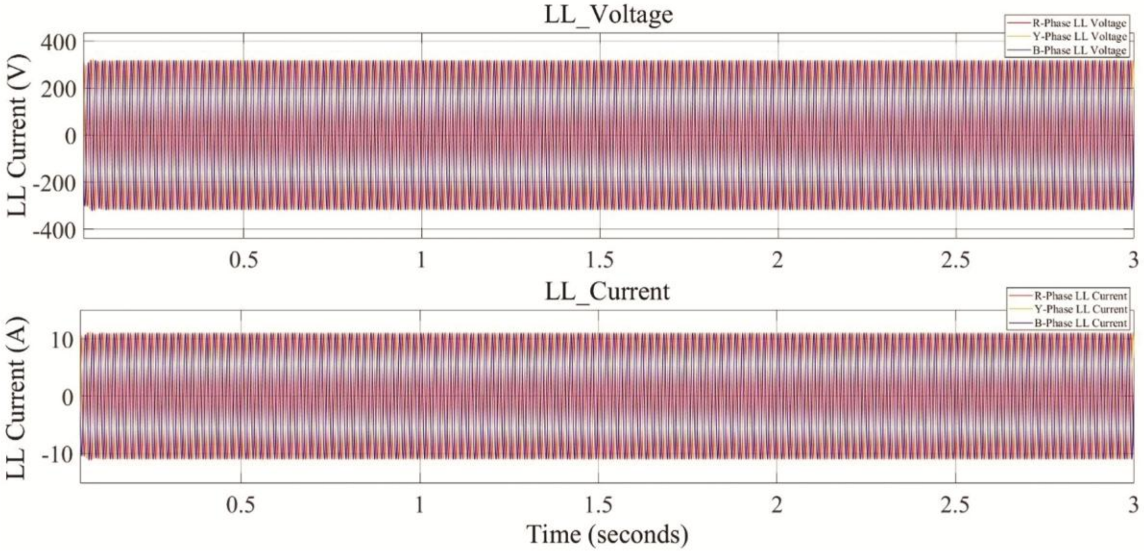

Fig. 4 — Steady-state voltage and current inputs to the local load

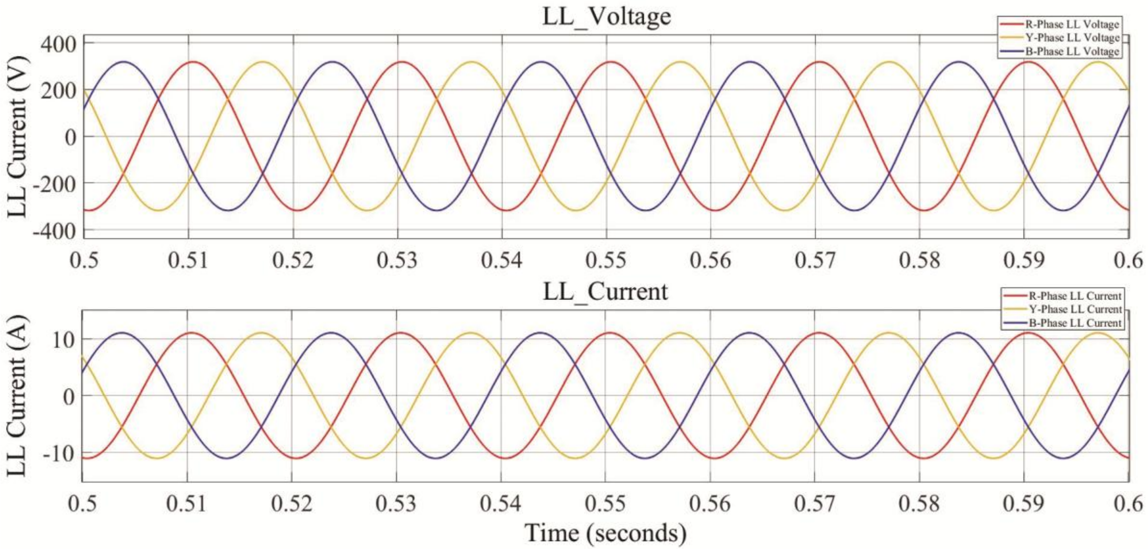

Fig. 5 — Instantaneous waveforms of voltage and current inputs to the local load

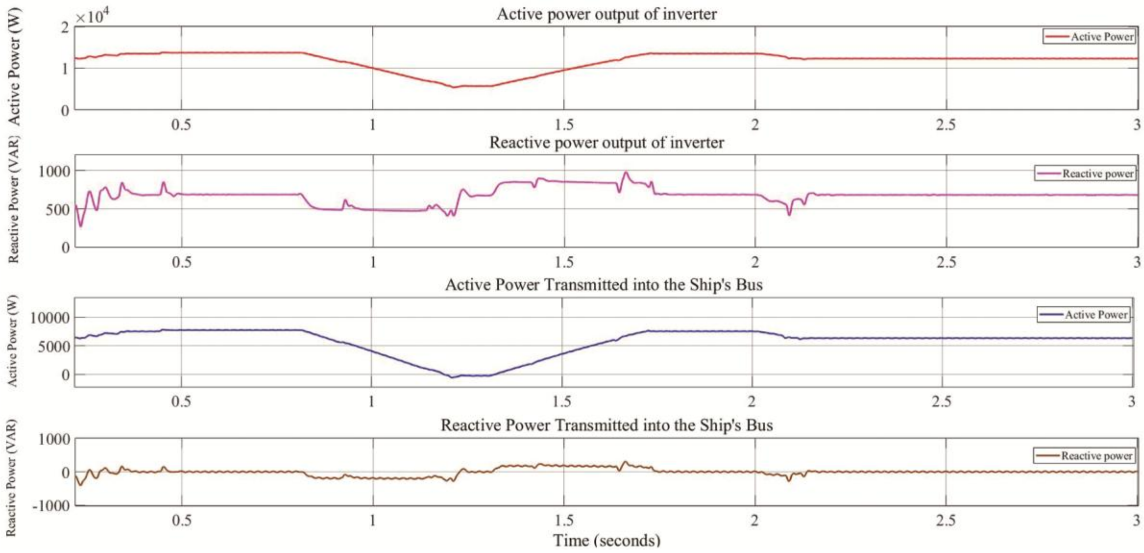

Fig. 6 — Active and Reactive power output of inverter and of power transmitted into ship's bus

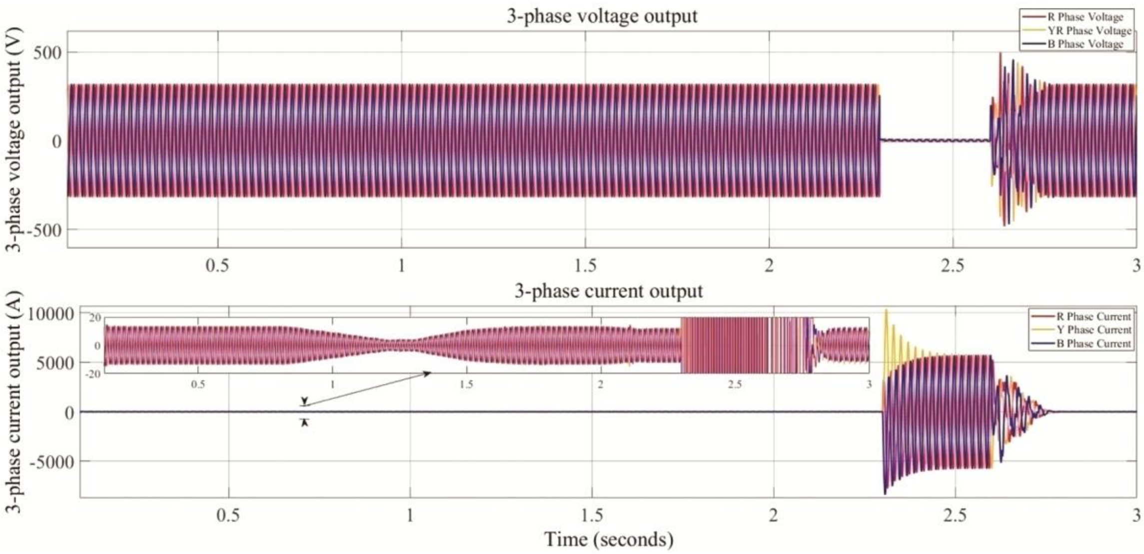

Fig. 7 — PV inverter's output during fault condition without protection scheme

terminal voltage and steady-state current values at the interconnection are within the limits.

Despite of desired operation of PV system, due to the switching action of circuit breaker, some transients can be observed in the inverter's output current waveform at the interconnection terminals. These transients occur for a very few time periods but after a long term use these transients can affect the circuit breaker.

In order to calculate the area covered, trapped energy, efficiency of PV array, efficiency of power converters, the calculation are as follows:

No. of PV modules = 50

Area covered by 1 module = 1.63 m^2

Area covered by 50 modules = 50 × 1.63 m^2

= 81.5 m^2

Efficiency of 1 PV module = 30.52 %

At STC (Standard Test Conditions),

Irradiance = 1000 W/m^2

Temperature = 25 °C

Inverter's output for 50 modules at STC,

V_{Phase} = 220 V

I_{Phase} = 20.8 A

Power (P_{Output}) = 3 × V_{Phase} × I_{Phase}

=13.5 kVA

Energy trapped in 81.5 m^2 area = 13.5 kVAh

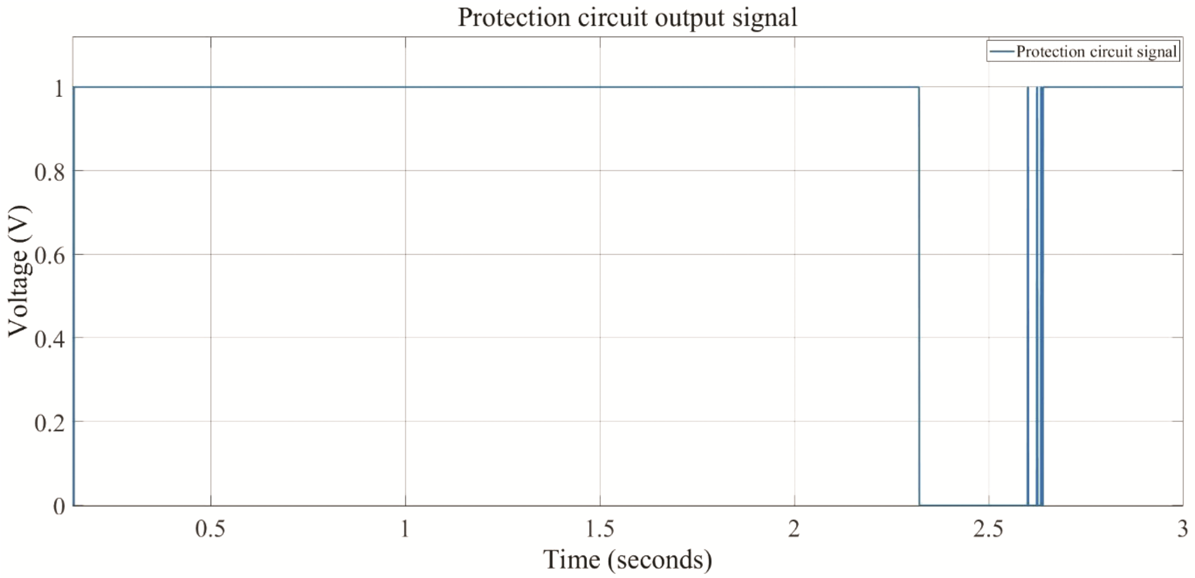

Fig. 8 — Protection circuit's steady-state output signal

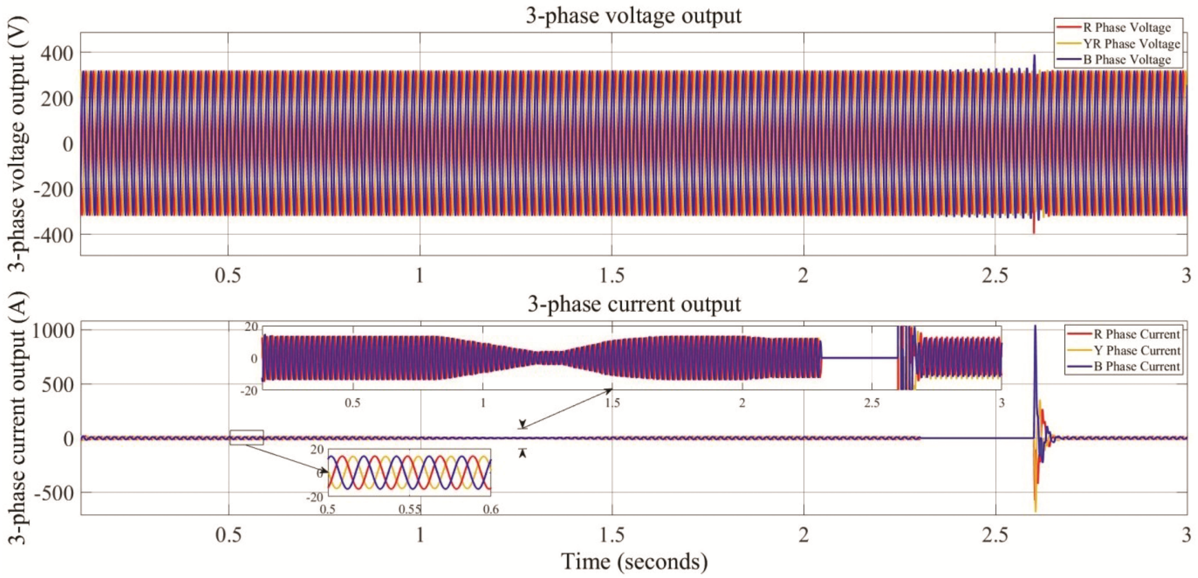

Fig. 9 — PV inverter's steady-state output during fault condition with protection scheme

Energy trapped per square meter area = 165.64 VAh/m^2

Efficiency of power converters =

$$\text{Inverter output}/_{\text{PV output}} \times 100$$

PV array's output power at STC = 50 × 305.2 W

= 15.26 kW

Inverter's output at STC = 13.5 kVA

Therefore, efficiency of power converters = 88.5 %

Discussion

Photovoltaic power generation is acquiring more implications as a source of renewable energy by reason of its numerous benefits. These benefits comprise of eternal green energy production system, effortlessness upkeep and many more. Nevertheless, their high installations cost is the downside. Furthermore, weather conditions, for instance the temperature, irradiance; sun shading and insolation level influences the PV panel output.

In the proposed system, variable irradiation and temperature levels are provided to the PV array using a signal generator block while simulation. Perturb and observe MPPT algorithm is a simple method of tracking the maximum power point of PV array. But the tracked power point oscillates around the actual maximum power point because of the limitation of having a fixed step to update the duty cycle of the flyback converter. This limitation can be eliminated by using incremental conductance modified with integral regulator MPPT technique.

High power flyback converter controlled by incremental conductance modified with integral regulator MPPT is helping in efficiently tracking MPP and cause very few oscillations around actual MPP. Also, High power flyback converter is providing electrical isolations b/w PV array & power converters and it helps the PV system to operate for different input voltage levels.

Utilization of DC input power by the Inverter is dependent on type of inverter and inverter control scheme. SVPWM control scheme is able to utilize 15 % more DC input power than that of sinusoidal pulse width modulation scheme and cause less THDs in the output voltage and current than that of SPWM. Also, SVPWM is able to synchronize PV inverter and electricity distribution system of marine ship by matching their voltages and frequencies.

Happening of the faults, for instance over voltage, under voltage, over current, under current, THD and frequency deviations can seriously damage the PV system and local load connected to it. In order to protect the system against these faults, the proposed protection circuit is able to sense and provide ON/OFF signal to circuit breaker and prevent the PV system from feeding power grid of ship during any of the above-mentioned faults including islanding. Also, to protect system from transient electrical noise and flow of DC component into the power grid of ship, an isolation transformer has been used to electrically isolate PV inverter and electricity distribution system of ship.

Conclusion

Power demand is growing gradually. To meet the energy demand, conventional energy sources are not sufficient because of environment concern and therefore, there is a need to exploit renewable energy sources for meeting the ever-increasing energy demands. The proposed system can be used to transmit solar power into the power grid of ship in a reliable and efficient manner. The system has the ability to efficiently trace the MPP of PV array, input DC voltage utilization by the inverter is 15 % more than that of SPWM controlled inverter. The system has electrical isolation between PV array and inverter, also between inverter and ship's power grid. The protection circuit of the proposed PV system can be trusted with the protection against different kinds of faults. This system will definitely prove to be a technology breakthrough for marine ships.

Supplementary Data

Supplementary data associated with this article is available in the electronic form at http://nopr.niscair.res.in/jinfo/ijms/IJMS_49(07)1132-1142_SupplData.pdf

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Conflicts of Interest

The authors declare no conflict of interest. No funding was involved in the presented research work and hence, no funders had any role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Author Contributions

Both the authors have contributed significantly in the presented research work. The simulation modelling, performance analysis and manuscript writing of the proposed system was carried out by SD. The mathematical modelling, manuscript editing and supervision of the proposed system was done by PN.

References

1 Georgakis D, Papathanassiou S, Hatziargyriou N, Engler A & Hardt C, Operation of a prototype microgrid system based on micro-sources equipped with fast-acting power electronics interfaces, *PESC Record - IEEE 35th Annual Power Electronics Specialists* Conference (Germany), 2004, pp. 2521-2526.

2 Lee J, Member S, Han B & Member S, Operational Characteristic Analysis of DC Micro-grid using Detailed Model of Distributed Generation, *Transmission and Distribution Conference and Exposition, IEEE PES* (United States), 2010, pp. 1-8.

3 Kanellos F D, Tsouchnikas A I, Hatziargyriou N D & Member S, Micro-Grid Simulation during Grid-Connected and Islanded Modes of Operation, *International Conference on Power Systems Transients, IPST'05* (Canada), 2005, pp. 113.

4 Katiraei F, Mauch K & Dignard-bailey L, Integration of Photovoltaic Power Systems in High-Penetration Clusters for

Distribution Networks and Mini-Grids, *Int J Distrib Energy Res*, 3 (3) (2007) 207-223.

5 Calais M, Agelidis V G & Meinhardt M, Multilevel converters for single-phase grid connected photovoltaic systems: An overview, *Sol Energy*, 66 (5) (1999) 325–35.

6 Kjaer S B, Pedersen J K & Blaabjerg F, A review of single-phase grid-connected inverters for photovoltaic modules, *IEEE T Ind Appl*, 41 (5) (2005) 1292–306.

7 Behrouzian E, Tabesh A, Bahrainian F & Zamani A, Power electronics for photovoltaic energy system of an oceanographic buoy, *IEEE Applied Power Electronics Colloquium* (Malaysia), 2011, pp.1-4.

8 Spagnolo G S, Papalilo D & Martocchia A, Eco friendly electric propulsion boat, *10th International Conference on Environment and Electrical Engineering, EEEICEU* (Rome, Italy), 2011, pp.1-4.

9 Park J S, Katagi T, Yamamoto S & Hashimoto T, Operation control of photovoltaic/diesel hybrid generating system considering fluctuation of solar radiation, *Sol Energy Mater Sol Cells*, 67 (1-4) (2001) 535–42.

10 Kobougias I, Tatakis E & Prousalidis I, PV Systems Installed in Marine Vessels–Technologies and Specifications, *Advances in Power Electronics*, 2013 (1) (2013) 1-8 .

11 Feng X, Zourntos T, Butler-Purry K L & Mashayekh S, Dynamic load management for NG IPS ships, *IEEE PES General Meeting* (USA), 2010, pp.1-8 .

12 Weiming M, Development of vessel integrated power system, *International Conference on Electrical Machines and Systems (ICEMS)* (China), 2011, pp.1-12.

13 Guarnieri M, The rise of light, *History of High-Technologies and their Socio-Cultural Contexts Conference (HISTELCON)* (Israel), 2015, pp.1-14.

14 Al-Masri H M, Abu-Errub A, Ayyad W R & Ehsani M, On the PV module characteristics, *International Symposium on Power Electronics, Electrical Drives, Automation and Motion* (Italy), 2016, pp. 901-905.

15 Xiong X & Shen A, Improved maximum power point tracking in PV system based on flyback converter, *Chinese Automation Congress (CAC)*(China), 2015, pp. 1211-1214.

16 Elasser A & Chow T P, Silicon carbide benefits and advantages for power electronics circuits and systems, *P IEEE*, 90 (6) (2002) 969-986.

17 Extremum O U R, Brunton S L, Rowley C W, Kulkarni S R & Clarkson C, Maximum Power Point Tracking for Photovoltaic Seeking Control, *IEEE Trans Power Electron*, 25 (10) (2010) 2531–40.

18 Esram T & Chapman P L, Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques, *IEEE Trans Energy Convers*, 22 (2) (2007) 439-449.

19 Jain S & Agarwal V, Comparison of the performance of maximum power point tracking schemes applied to single-stage grid-connected photovoltaic systems, *IET Electr Power App*, 1 (1) (2007) 753–762.

20 Femia N, Petrone G, Spagnuolo G & Vitelli M, A Technique for Improving P & O MPPT Performances of Double-Stage Grid-Connected Photovoltaic Systems, *IEEE Trans Ind Electron*, 56 (11) (2009) 4473–82.

21 Abdulkadir M, Samosir S, Yatim H M & Yusuf S T, A New Approach of Modelling, Simulation of MPPT for Photovoltaic System in Simulink Model, *ARPN J Eng Appl Sci*, 8 (7) (2013) 488–94.

22 Bai H, Zhao Z, Meng S, Liu J & Sun X, Comparison of three PWM strategies -SPWM, SVPWM & One-cycle control, *The Fifth International Conference on Power Electronics and Drive Systems* (Singapore), 2003, pp. 1313-1316.

23 Kumar K V, Michael P A, John J P & Kumar S S, Simulation and Comparison of Spwm and Svpwm Control for Three Phase Inverter, *ARPN J Eng Appl Sci*, 5 (7) (2010) 61–74.

24 Varier R & Pindoriya N M, A novel active anti-islanding protection scheme for grid-interactive roof-top solar PV system, *18th National Power Systems Conference, NPSC* (Guwahati, India), 2014, pp. 1-6.

25 Banu I V & Istrate M, Islanding prevention scheme for Grid-Connected Photovoltaic systems in Matlab/Simulink, *Universities Power Engineering Conference* (Australia), 2014, pp. 1-6.

26 Basso T S & DeBlasio R, IEEE 1547 series of standards: Interconnection issues, *IEEE Trans Power Electron*, 19 (5) (2004) 1159–1162.

27 Dhiman S & Nijhawan P, Design & analysis of improved bus-tied photovoltaic system for marine ships, *Indian J Geo-Mar Sci*, 48 (12) (2019) 1963-1970.

28 Tedde M & Smedley K, Anti-islanding for three-phase one-cycle control grid tied inverter, *IEEE Trans Power Electron*, 29 (7) (2014) 3330–3345.