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Single-Stage Inverter cum Chopper (Ssicc) For Pv-Battery System

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Abstract
This paper introduces a single stage inverter cum chopper (SSICC). This SSICC finds wide applications in grid connected solar system since it uses single stage conversion instead of multistage conversion, reduced losses, low cost, simple in construction, improved efficiency and reduced volume .The main concept of the SSIC is to prefer single stage power converter on behalf of multistage converter for dc/ac and dc/dc operation for solar energy storage applications.
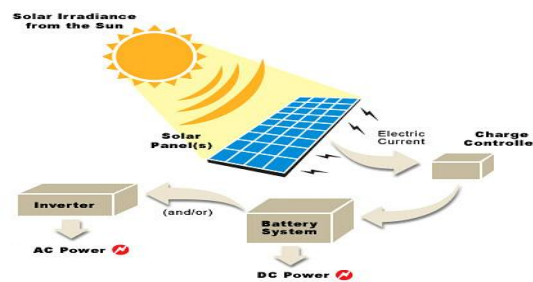
Index Terms— Photovoltaic (PV) system, Maximum power point tracking, Power Converter, energy storage system.

I. INTRODUCTION

The output of solar system is not a continuous process it is time dependent & intermittent energy resource .It depends on the insolation, time of the day, direction of sunlight and the weather conditions. The output of solar system falls dramatically when a portion of solar panel gets covered. Due to stability point of view an energy source that can be that can deliver power at the request are desired. As a result, energy storage such as batteries should be connected to solar systems to improve the performance of solar systems. There are different techniques for connecting energy storage to solar system. The techniques used till now for power conversion may consist of increased conversion stages. Every techniques has its merits and demerits .Therefore every technique should be distinguished with regard to the conversion stages, efficiency, cost, construction & circuit complexity, etc.

This paper initiates an SSICC. SSICC perform different operation such as DC-DC &DC-AC .Part II introduces the proposed SSICC, operating modes, and system benefits. In Part III, operation of the proposed technique, refinement to previous techniques are discussed. Part IV verifies the proposed system with the help of simulation & MATLAB to evaluate the performance characteristics. Part V summarizes and concludes the paper.
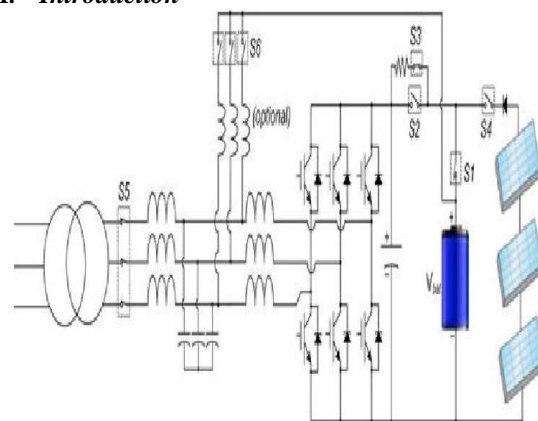
II. PROPOSED SSICC

A. Introduction

Fig. 2. Diagram of the proposed SSICC circuit.

The SSICC is basically a three-phase PV inverter. Fig. 2 shows the diagrammatic view of SSICC. The SSICC provides changes to the conventional three-phase inverter system. These changes allow the proposed system to utilize the conventional three-phase inverter system to operate as both chopper & inverter for integration of solar energy system with the batteries. The SSICC is a three-phase voltage source converter and its associated components, the proposed system requires

optional inductors in addition to ac filter inductance

B. Switching states of the proposed system

The five possible operation modes for the proposed system are as fallows.
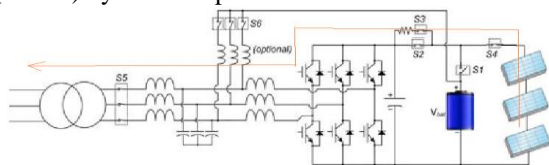
(a) Mode 1—PV to grid (S_1 and S_6 switches remain open)

**(b)Mode 2—PV to battery (switch S_6 close & S_5, S_3 open)**

(c) Mode 3—PV/battery to grid (switch S_6 open & S1, S2, S3, S4 & S_5 close)

**(d) Mode 4—battery to grid (switch $S_1, S2, S_3$ & S_5 close & S_4, S_6 open)**

(a)In Mode 1, the solar panels are directly connected to the grid with maximum power point tracking (MPPT) by a dc/ac operation of the SSICC.
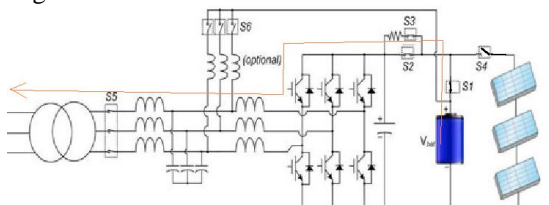

(b)In Mode 2, the solar panels charge the batteries through dc/dc operation of the converter. In this mode it is possible to track maximum power with the help of MPPT algorithm.
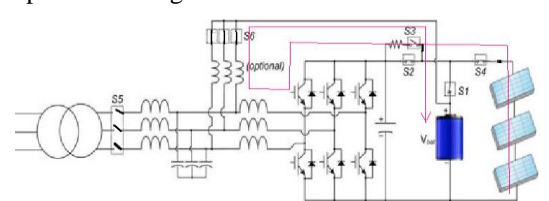
(c)In Mode 3 both the solar panels & batteries are connected to the grid by closing the switch S_1.
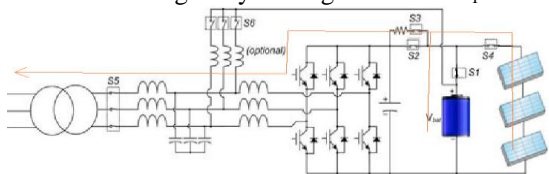
(d)Mode 4 delivers the energy stored in the battery to the grid.

C. Advantages of SSICC

The SSICC provides significant merits to solar power plants. The current state-of-the-art technology is to integrate the energy storage into the ac side of the solar system. It can be utilized as a mean for shifting peak hours to solar power plants. This technique allows the system owners to have a

suppose is not enough for the charging purpose.

strong asset which helps them to plan and operate the power plant with respect to their needs. The SSICC has reduced conversion stages, high efficiency, low cost & simple in design etc.
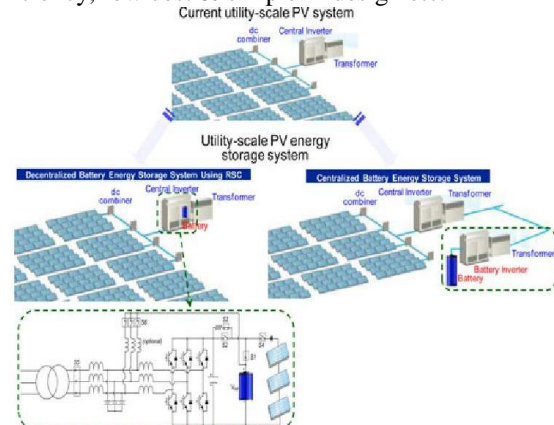

Fig. 3. Solar energy storage systems with the SSICC and the state-of-the-art solution

D. SYSTEM CONTROL SCHEMES

In response to the request of the grid operator, different system control techniques can be realized with the SSICC solar power plants & are as follows:

1)system control 1 for $P_{gen} > P_{req}$;
2)system control 2 for $P_{gen} < P_{req}$;
3)system control 3 for $P_{gen} = P_{req}$;
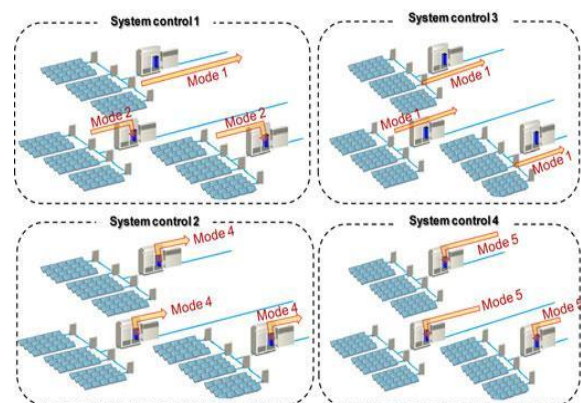4) system control 3 for $P_{gen} = 0$;

Fig. 5. System control schemes

III. SINGLE STAGE CONVERTER CONTROL

A. Control of the proposed system in DC/AC operation modes (modes 1, 3 &4)

The dc/ac operation of the SSICC is utilized for delivering power from PV to grid, battery to grid, PV and battery to grid, and grid to battery. The single stage converter performs the MPPT algorithm to deliver maximum power from the PV to the grid. Like the conventional solar inverter control, the SSICC is implemented in the synchronous reference frame. The synchronous reference frame

proportional-integral current control is employed. In a reference frame rotating synchronously with the fundamental excitation, the fundamental excitation signals are transformed into dc signals. As a result, the current regulator forming the innermost loop of the control system is able to regulate ac cur-rents over a wide frequency range with high bandwidth and zero steady-state error. For the pulse width modulation (PWM) scheme, the conventional space vector PWM scheme is utilized. Fig. 6 presents the overall control block diagram of the single stage converter in the dc/ac operation. For the dc/ac operation with the battery, the proposed system control should be coordinated with the battery management system (BMS), which is not shown in Fig. 6.

B. Control of the proposed system in DC/DC operation modes (modes 2)

The dc/dc operation of the single stage converter is also utilized for delivering the maximum power from the solar panels to the battery. The SSICC in the dc/dc operation is a boost converter which controls the current flowing into the battery. In this paper, Li-ion battery has been selected for the solar energy storage systems due to its advantages. Li-ion batteries are charged in two stages

1. CC
2. CV

CC: Applying constant charging current to the battery, until the voltage limit per cell is reached.
CV: Apply a constant voltage equal to the maximum cell voltage with respect to the number of cells in series with the battery, as the current gradually falls to chase 0, until the current is less than a set threshold value of about 3% of initial constant charging current.

Thus, the dc/dc converter used in charging process must be capable of giving stable control for maintaining either current or voltage at a constant value, depending on the status of the battery. Normally certain capacity losses occur if constant voltage charging is not preferred. However, it is not necessary to avoid constant current charging to simplify the charging control and process. The latter technique can be used to charge batteries, from the control point of view, it is just enough to control only the inductor current. Therefore for charging the Li-ion batteries the SSICC performs the MPPT algorithm to deliver maximum power from the solar panel to the battery in the dc/dc operation. Fig. 7 shows the overall control circuit of the single stage converter in the dc/dc operation.
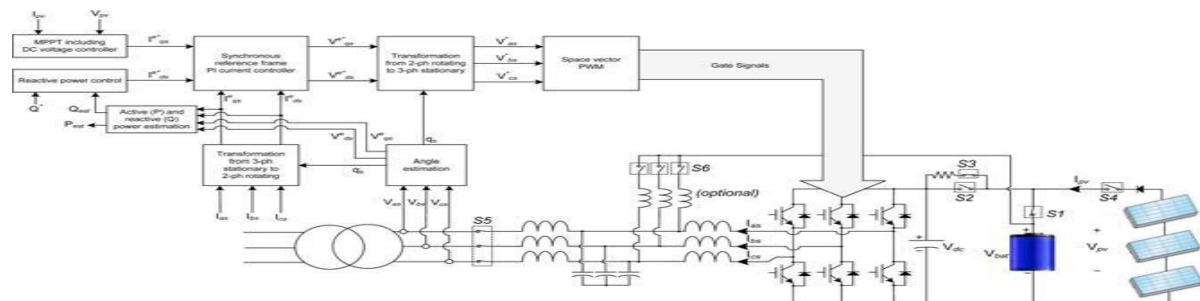

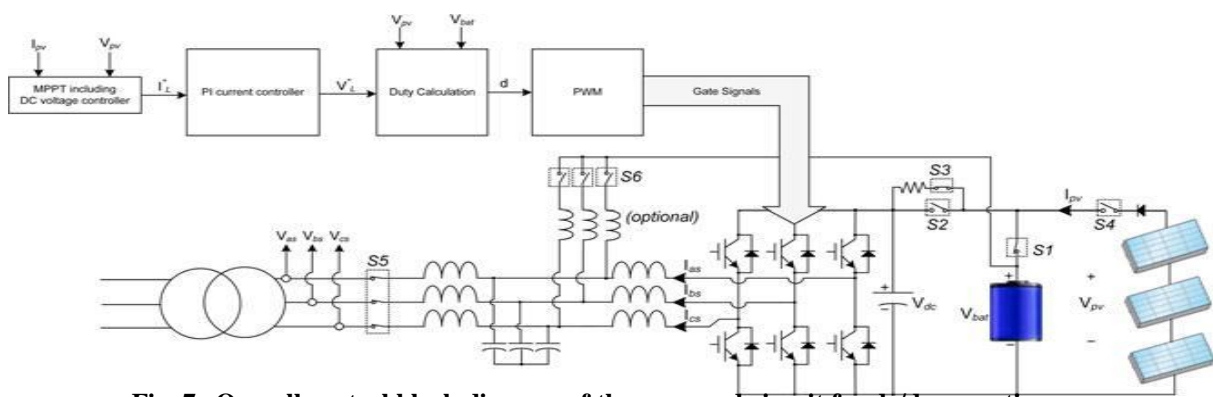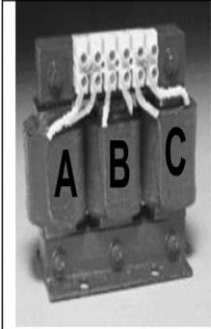**Fig. 5. Overall control block diagram of the proposed circuit in dc/ac operation.**

Fig. 7. Overall control block diagram of the proposed circuit for dc/dc operation.

C. Design considerations and modifications to conventional three phase inverter for solar battery system:

One of the most important requirements of the paper is that the proposed solution must have minimal complexity and modifications to the conventional three-phase solar converter system.

Therefore, it is necessary to investigate how a three-phase dc/ac converter operates as a dc/dc converter and what modifications should be made. It is common to use a *LCL* filter for a high-power three-phase PV converter .Therefore the SSICC in the dc/dc operation is expected to use the inductors already available in the *LCL* filter. There are basically two types of

inductors, coupled three-phase inductor and three single-phase inductors that can be utilized in the single stage converter circuit.

DC Application	Inductance value
Only A	1.42 mH
Only B	1.58 mH
A & C	0.50 mH
A & B & C	0.13 mH

TABLE I
INDUCTANCE VALUE OF A COUPLED THREE-PHASE INDUCTOR IN THE DC/DC OPERATION

Using all three phases of the coupled three-phase inductor in the dc/dc operation causes a significant drop in the inductance value due to inductor core saturation. Table I presents an example of inductance value of a coupled three-phase inductor for the dc/dc operation, which shows significant drop in the inductance value. The reduction in inductance value requires inserting additional inductors for the dc/dc operation which has been marked as "optional" in Fig. 2. To avoid extra inductors, only one phase can perform the–dc/dc operation. However, when only one phase, for instance phase B, is utilized for the dc/dc operation with only either upper or lower three insulated-gate bipolar transistors (IGBTs) are turned OFF as complementary switching, the circulating current occurs in phases A and C through filter capacitors, the coupled inductor, and switches, resulting in significantly high current ripple in phase B current, as shown in Fig. 8.

To prevent the circulating current in the dc/dc operation, the following two solutions are proposed;

1) All unused upper and lower IGBTs must be turned OFF;
2) The coupled inductor is replaced by three single-phase Inductors.
While the first solution with a coupled inductor is straight-forward, using three single-phase inductors

makes it possible to use all three phase legs for the dc/dc operation. There are two methods to utilize all three phase legs for the dc/dc operation:
1) Synchronous operation;
2) Interleaving operation.

In the first solution, all three phase legs can operate synchronously with their own current control. In this case, the battery can be charged with a higher current compared to the case with one-phase dc/dc operation. This leads to a faster charging time due to higher charging current capability. However, each phase operates with higher current ripples. Higher ripple current flowing into the battery and capacitor can have negative effects on the lifetime of the battery and capacitors.

To overcome the aforementioned problem associated with the synchronous operation, phases B and C can be shifted by applying a phase offset. For the interleaving operation using three phase legs, phases B and C are shifted by 120° and 240°, respectively. The inductor current control in interleaving operation re requires a different inductor current sampling scheme, as shown in Fig. 9. However, for three-phase interleaving, a modified sampling scheme is required to measure the average currents for all three phases. Therefore, the sampling points for phases B and C must be shifted by 120° and 240°, respectively [see Fig 9(b)], which may imply that computation required inductor current control for each phase should be done asynchronously. Using the interleaving operation reduces the ripples on the charging current flowing into the battery. Therefore, the filter capacitance value can be reduced significantly.

D. Mode Change Control

The basic concept of the SSICC is to use a single power electronics circuit to perform different operation modes such as PV to grid (dc to ac) and PV to battery (dc to dc) for PV systems with energy storage, as discussed earlier. Therefore, in addition to the converter control in each mode, the seamless transition between modes is also essential for the single stage converter operation. To change a mode, the single stage converter must be reconfigured by either disconnecting or connecting components such as the battery through contactors.
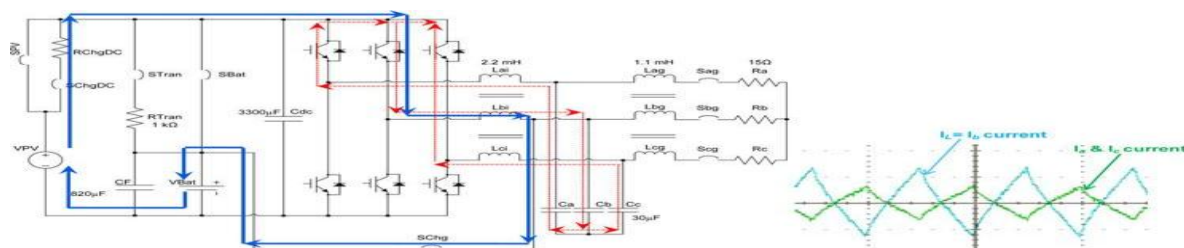

Fig. 8.   Circulating current path if one phase is used for the dc/dc operation of the proposed circuit with a coupled three-phase inductor.
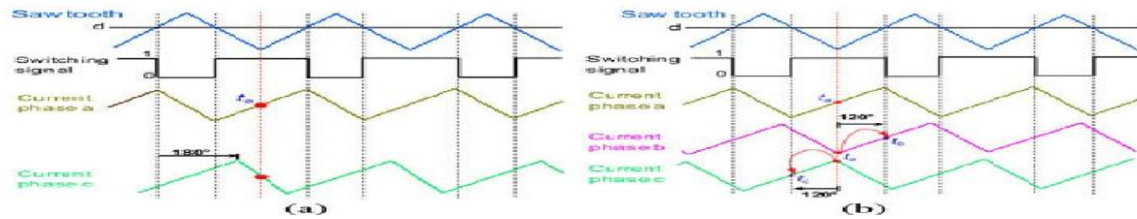
Fig. 9. Inductor current sampling schemes in the interleaving operation.
(a) Two-phase interleaving. (b) Three-phase interleaving.

It is very important to understand the dynamics of the SSICC. Generally, it is necessary to understand the relay response time such as how much time it takes for a relay to completely close or open. Hence, the performance curves of all re-lays used in the SSICC circuit must be investigated. All relays used in the SSICC circuit have a maximum operating time equal to or smaller than 50 ms. All switching, which occur during mode change, are done under zero or nearly zero current, except fault cases. To verify the operating time given in the datasheet of the relays, a test for one of the relays used is made. The operating time of the relay used for SChgDC in Fig. 8 is investigated during pre charging of the inverter capacitors. The captured waveforms are shown in Fig. 10.The relay signal inside the DSP is captured through a D/A converter. It takes 240 μs until the signal reaches a value, 12 V, that is high enough to trigger the relay switching. Once the operating voltage is applied to the relay, it takes 20 ms until the current starts flowing through the relay. In other words, it takes 20 ms for the relay to be fully closed. The measured relay operating time of 20 ms is only half of the value given in the datasheet. For all relays used in the circuit, 80 ms is used as the relay switching transient time for both closing and releasing.
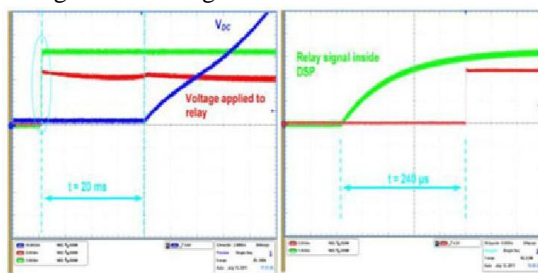
The highest layer of the RSC mode change control is shown in Fig. 11. This layer consists of fault detection, fault reset, and normal operation. The basic fault detection such as detecting over current and overvoltage and fault management like turning off PWM signals are implemented inside the converter control executed in the inner most control loop. In this way, fast fault detection and protection are possible.
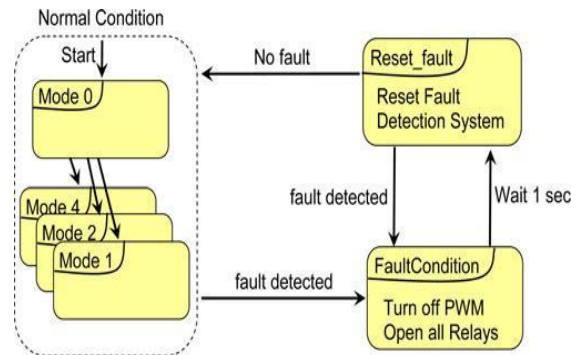
In general, shutting down all PWM signals is able to clear the fault. In addition, all relays are forced to be opened. If the system is operating normal, the status of the system will be "Normal Condition." Once the fault flag is set by detecting a fault, the status of the system will be changed to "Fault Condition." In this status, all relays as well as PWM signals are turned off. When the system is in "Fault Condition," the single stage converter control tries to clear a fault condition every 1 s. If a fault cannot be cleared, the system will remain in the "Fault Condition." If a fault is cleared, "Normal Condition" will be reinstated. Inside "Normal Condition," the system always starts with Mode 0, which is the shutdown mode. This allows the single stage converter to move to a new mode safely, after a fault is cleared.
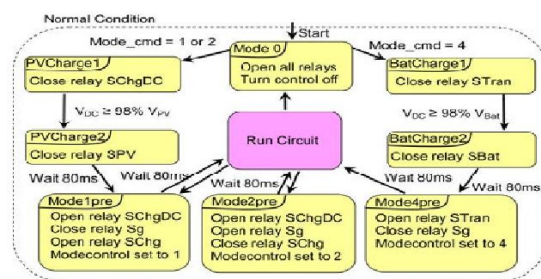

Fig. 12. States inside "Normal Condition."

The control topology inside "Normal Condition" is presented in Fig. 12. The single stage converter control mode can be changed to any mode from the present mode. If Modes 1 or 2 are commanded, the state will change from "Mode 0" to "PVCharge1" and relay "SChgDC" will be closed. This will charge the capacitor "C_{dc}" through the resistor "RChgDC." Once the dc voltage of the capacitor reaches 98% of the source voltage, the state

will change to "PVCharge2."

This will also close relay "SPV," while the re-lay "SChgDC" will remain closed, because no new action refers to this relay. To make sure that the relay "SPV" is fully closed, a delay of 80 ms, relay switching transient time, is used, as discussed earlier. For example, the procedure of Mode 1 is described. Let us assume that the current state is "Mode1pre." The relay "SChgDC" is opened, so that the pre charging procedure is completed. Also, the three grid-switches "Sag," "Sbg," and "Scg" are closed and therefore the load is connected to the single stage converter. Furthermore, the relay "SChg" is opened and the control is set to Mode 1, which is dc/ac control. Because relay switching is included in the state "Mode1pre," a delay of 80 ms is required to move to the state of "Run Circuit." When the previous mode is 1, it is possible to directly move to "Mode2pre."

This would bypass the pre charging process since the capacitors of the inverter are required to be connected to the PV side in both modes. All the actions from "Mode2pre" shown in Fig. 12 are executed. After 80 ms, the state moves to "Run Circuit" shown in Fig. 13. When the previous mode is Mode 2 and the new mode is Mode 1, the state directly moves from "PWMOFF" to "Mode1pre" and back to "Run Circuit" by avoiding the pre charge process.
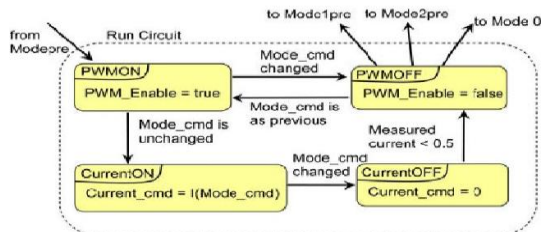

The startup of Mode 4 is different from Modes 1 and 2, be-cause it connects the battery to the inverter instead of connecting the PV to it. But the pre charging procedure is quite the same. Only different relays are used—"STran" for charging the capacitor "C_{dc}" through the resistance "RTran" and relay "SBat" for directly connecting the battery to the inverter. Then, the state "Mode4pre" closes the grid switches and sets the mode control to number 4, which is again dc/ac control.

After "Mode4pre," the state changes to "Run Circuit." Going from Modes 1 or 2 to Mode 4 or vice versa is not as easy as the mode change between Modes 1 and 2. The dc voltage always has to be changed to either the battery voltage (coming from Mode 1 or 2) or the PV voltage (coming from Mode 4), which makes the mode change control to use Mode 0 for transition. This does not mean that the circuit needs to be fully de energized, since the pre charging resistances limit the current and can therefore take care of this process.
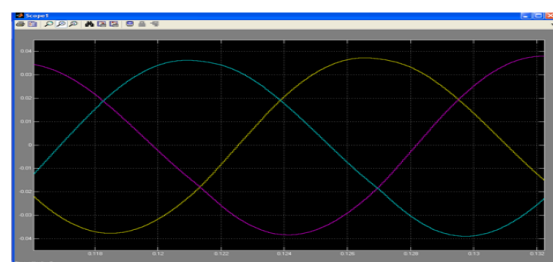
IV. PERFORMANCE CHARECTERISTICS OF SSICC

The proposed system control algorithms are verified with the help of MATLAB/Simulink. The performance of the SSICC in different operation modes has been tested with the help of MATLAB/Simulink to analyze the performance of SSICC.
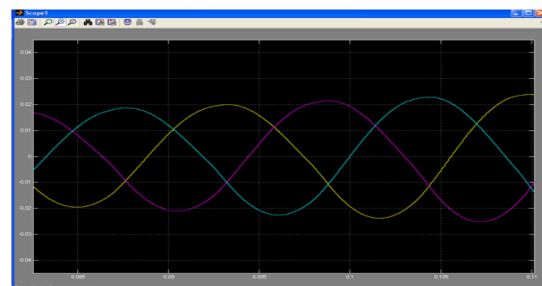
A. Simulation results of the proposed system in DC/AC Operation Modes
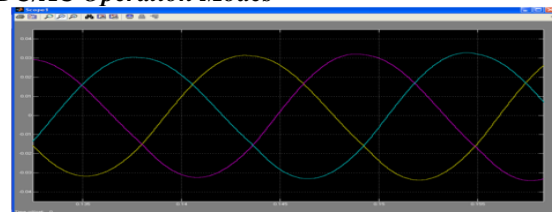

(a)

(b)

(c)

Steady-state performance operating modes for the proposed system in DC /AC. (a) Mode 1—PV to grid (b) Mode 3—PV/battery to grid. (c) Mode 4—battery to grid.

The above figure shows the steady-state performance of dc/ac control in Mode 1. In this test, the voltage on the dc side V_{DC} of the inverter is set to 200 V. The current reference is set to 5 A_{peak} for the frequency of 60 Hz. Fig. a shows the steady-state performance of dc/ac control in Mode 1.. In Fig. b, shows the steady-state performance of dc/ac control in Mode 3. The average battery charging current is 1.8 A. The battery charging current has about 0.85 A_{pk-pk} current ripple with the frequency of 60 Hz.

C. Simulation results of the proposed system in DC/DC Operation Mode
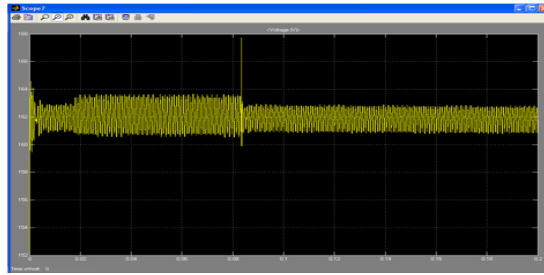
(a)

Steady-state performance operating modes for the proposed system in DC /DC. (a) Mode 2—PV to Battery.

In Mode 2 (PV to battery), the three-phase inverter is used as a dc/dc converter. As explained, initially a coupled three-phase inductor is used for the filter inductor to the inverter side. When only phase B is utilized for the dc/dc operation with only either upper or lower three IGBTs are turned off as complementary switching, the circulating current occurs in phases A and C through filter capacitors, the coupled inductor, and switches, resulting in significantly high current ripple in phase B current, as shown in Fig. 18(a). To solve the aforementioned problem, as explained, two solutions are proposed. First, the switches un-used are turned off and consequently the phase current presents much lower ripple as shown in Fig. (b). The average current in phase B is now 5 A with a ripple of 5 A_{pk-pk} while the current in phases A and C remains zero. This means no circulating current. The second solution is to use three single-phase inductors in the SSICC circuit. As expected with single-phase operation in this mode, the circulating current is vanished automatically. The result of the test is presented in Fig. (c) Show that the current in the other phases remains zero while the battery is charged.

The average phase B current is 5 A and the average battery current is also 5 A. The phase B ripple is 5 A_{pk-pk} and the battery current ripple is 1.4 A_{pk-pk} . The capacitor ripple current is about 4.2 A_{pk-pk} ·

Using three single-phase inductors enables the SSICC to use all three phase legs in the dc/dc operation. As discussed earlier, there are two methods to utilize all three phase legs for the dc/dc operation. In the first approach, all three phase-legs operate synchronously with their own current controls.

The sum of all three phase currents is 5 A, which means that each phase carries one-third of it. Therefore, it is possible to charge the battery with even a higher current, which leads to a faster charging time. However, each phase current shows the current ripple of 5 A_{pk-pk} · The battery current has the current ripple of 4 A_{pk-pk} and the capacitor current shows the current ripple of 12 A_{pk-pk} which is almost three times as high as the ripple current of the battery charging using a single phase leg. Higher

ripple current flowing into the battery and capacitor can have negative effects on the lifetime of the battery and capacitors.

As discussed earlier, using the interleaving operation can reduce the ripples on the charging current flowing into the battery. Battery current has a ripple current of 0.5 A_{pk-pk} and the capacitor current has a ripple current of 1.5 A_{pk-pk} when the sum of all three phase currents is 5 A and the average battery current is 5 A. These current ripples are one-third of the ripple currents for dc/dc control using a single phase leg and one-eighth of the ripple currents for dc/dc control using all three phase legs in synchronous operation, which means significant ripple reduction is achieved by interleaving operation.

V. CONCLUSION

This paper proposed a single stage inverter cum chopper for solar- battery application, particularly utility-scale solar-battery application for solar applications. The proposed solution is also suitable to other intermittent energy sources including wind energy. The proposed solution requires simple circuit complexity therefore; the solution is very attractive for solar-battery application, because it has reduced conversion stages, improved efficiency and reduced cost, weight, and volume.

The basic concept of the proposed system is to use a single power conversion system instead of multistage conversion system to integrate solar panels with energy storage and grid.. Test results have been presented to verify the concept of the proposed system and to demonstrate the attractive performance characteristics of the proposed system. These results confirm that the proposed system is highly suitable for intermittent energy storage systems.

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