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Review of three port micro-inverter with power decoupling capability for photovoltaic (PV) systems applications

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The Photovoltaic (PV) systems have been realized using different architectures, starting with the string and centralized PV system to the modular PV system. Presently, decentralized inverters are being developed at the PV panel power level (known as AC – PV Modules). Such new PV systems are becoming more attractive and many expect this will be the trend of the future. The AC-Module PV system consists of an inverter attached to one PV panel. This integration requires that both devices have the same life-span. Although, the available commercial inverters have a relatively short life-span (10 years) compared to the 25 –year PV. It has been stated in literature that the energy storage capacitor (electrolytic type) in the single-phase inverter is the most vulnerable electronic component. Hence, many techniques such as (power decoupling techniques) have been proposed to solve this problem by replacing the large electrolytic capacitor with a small film capacitor. This paper will present a quick review of these power decoupling techniques, and proposes a new three-port micro-inverter with power decoupling capability for AC-module PV system applications.

Keywords: *AC-Module, MPPT, power decoupling, fly-back converter.*

1.0 INTRODUCTION

In both, stand-alone and grid-connected DG systems, an interface stage between them and the end user is needed to convert the generated power to a usable form. Power electronic plays an important role in the field of modern electrical systems that based on renewable sources. Renewable energy sources generate either DC or variable frequency AC and require some form of power conversion to generate a form that is compatible or required by the end user. Power electronic is an essential part for the integration of renewable energy system to achieve high efficiency and performance in power systems. The main goal of the power electronics technology is to convert electrical power from one stage to another stage as efficient as possible with a high level of intelligence.

In view of the fact that photovoltaic (PV) grid-connected system generates a DC power and DC/AC conversion stage (Inverter) must be used to convert the generated DC power into an acceptable AC power. The output of this stage has to satisfy all the standards required by the utility grid. In the subsequent sections we will explore the developments that have been done on the PV systems.

1.1 Grid-Connected Photovoltaic (PV) System

For grid-connected applications, there are several standards that must be guaranteed by the power inversion stage in the PV system. The dc-injected currents, total distortion harmonic (TDH), power factor, detection of islanding operation, and other

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factors all of them are governed by standards like IEEE 1547, IEC 61727 [10] and NEC 690. These standards aim to guarantee that the MIC injects high quality power to the grid. The power inversion stage in the grid-connected PV system must accomplish some or all of the following tasks:

- Maximum Peek Power Tracking, MPPT
- Power decoupling
- Boost the PV dc input voltage
- DC-AC power conversion
- Provide interfacing between the PV side and the grid side (electrical isolation and detection of islanding operation)

2.0 AC-MODULE PV SYSTEM

The AC-module PV system is shown in Figure 1, where one DC/AC converter is attached to the PV panel. The definition of the AC-module is given as:

An AC-module is an electrical product and is the combination of a single module and a single power electronic inverter that converts light into electrical alternating (AC) power when it is connected in parallel to the network. The inverter is mounted on the rear side of the module or is mounted on the support structure and connected to the module with a single point to point DC cable. Protection functions for the AC side (e.g. voltage and frequency) are integrated in the electronic control of the inverter [8-9].

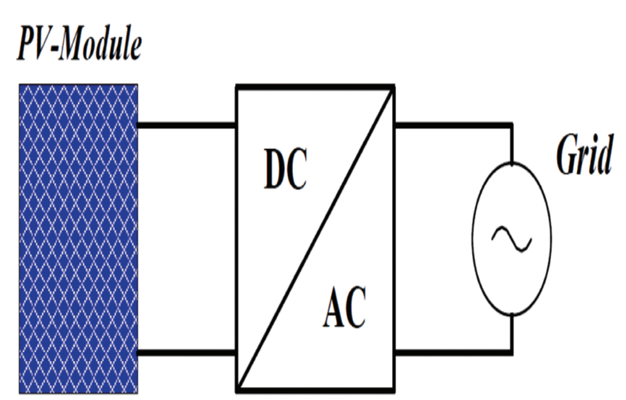

FIG. 1 AC-MODULE PV SYSTEM.

It is believed that this approach will be the trend for the future PV industry. In this kind of PV system, the MPPT problem is completely solved since each PV panel is connected to one inverter that has an MPPT. The AC-Module PV system offers Plug-N-Play concept. This option gives a high order of flexibility. This flexibility in the system makes it more common and easy to be used for end user application. Moreover, the modularity provided by the AC-Module PV system makes the future expansion of the whole system easier.

The available PV panels in the market, mono- and multi-crystalline silicon, have a MPP voltage in the range from 23 V to 38 V and 45 V at open circuit; 160 W-300 W [1-3]. Therefore, it is desirable that the power electronic inverter in the AC-Module can operate in wide input voltage range to adapt the wide output voltage range of the PV panel, which may make the optimization design more challenging. Because of the low output voltage for the PV panel an amplification stage before the inversion process becomes indispensable. Either transformer or a DC/DC converter is used to accomplish the amplification; where the DC input voltage is amplified to a voltage level compatible with the grid voltage. Plug-N-Play concept that enhances the flexibility of the PV system requires that the power electronics stage (the inverter) is integrated with the PV panel as it is stated in the definition of the AC-Module, so that it is called module integrated converter (MIC) in many references. Hence, the reliability (life-span), weight, and volume of the inverter become more important and have a vital role on the system. The life-span of the inverter should be comparable to that of the PV panel; which is more than 20 years. The available (commercial) inverters used in AC-Module PV-system have a life-span less than the PV panel; about 3-6 years. Although, many researches have been done to solve this issue and find a new inverter with high life-span, yet this problem is one of the biggest challenges that researchers trying to solve it. The reliability of the inverter is measured by two indices, mean time to first failure (MTFF) and mean time between failures (MTBF). Inverters nowadays have 5 years for MTFF and 10 years for

MTBF. The most vulnerable parts in the inverter are the power switches and the power decoupling capacitor; which have a strong impact on its life-span. The latter is the subject of this thesis and it will be discussed in more details in next chapters [4][5][6].

2.1 The cost Issue

The cost of the AC-Module PV system can be studied from two perspectives. The cost of the micro-inverter (MIC) alone and the cost of the AC-Module system as one package (the MIC and the PV panel). Due to low power level for the micro-grid inverter the cost per watt is high. The manufacturing cost will be reduced if a mass production is achieved. This is feasible in the AC-Module PV-system case since it is intended to be mass produced. Another feature for the AC-Module that also will reduce the overall cost comes from the fact that the MIC is connected directly to the grid with Plug-N-Play feature, which means that dc cabling and installation expertise are not necessary any more. This in turn reduces (or even eliminates) the cost of installation. Figure 2 shows that about 1/3 (32%) of the cost of a PV system is for installation. By reducing this cost, the one can pay more on the MIC [14].

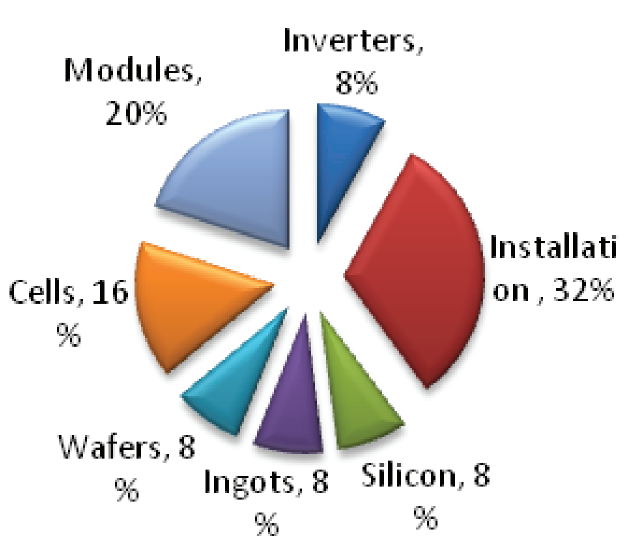

FIG. 2 COMPOSITION OF THE PHOTOVOLTAIC POWER COSTS

3.0 DOUBLE-FREQUENCY POWER RIPPLE IN SINGLE PHASE MICRO-INVERTER AND POWER DECOUPLING SOLUTION

The double-frequency power ripple problem in single-phase grid-connected inverter is explored. It also presents different power decoupling techniques that aim to solve power ripple problem along with a reasonable comparison between them.

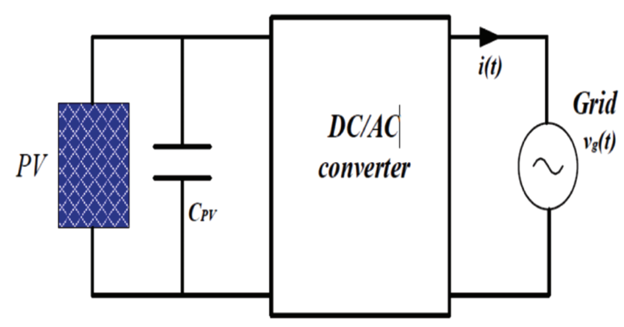

FIG. 3 SINGLE-PHASE INVERTER ARCHITECTURE

In grid-connected single-phase inverter shown in Figure 3, assume that the injected current to the grid is given in Figure 3 and the grid voltage which is given in Figure 4.

$$i(t) = I\sin(\omega_0 + \varphi) \qquad ....(1)$$

$$v_g(t) = V_g\sin(\omega_0 t) \qquad ....(2)$$

Where ω_0 is the grid frequency and φ is the phase difference between the injected current and the grid voltage; which is desired to be zero for unity power factor operation. The instantaneous output power $P_0\ (t)$ is given as follows:

$$P_0(t) = V_g(t) \times i(t) \qquad ....(3)$$

$$P_0(t) = \frac{1}{2}V_g\cos(\varphi) + \frac{1}{2}V_g I\cos(2\omega t + \varphi) \qquad ....(4)$$

If φ=0, then $P_0\ (t)$ will be

$$P_0(t) = \frac{1}{2}V_g I + \frac{1}{2}V_g I\cos(2\omega t) \qquad ....(5)$$

The instantaneous power consists of two terms. The average output power $P_{o_{av}}=\frac{1}{2}V_gI;$ which is constant. The second term $P_{o_{avc}}(t)=\frac{1}{2}V_gI\cos(2\omega t);$ is a time varying term with a twice line frequency oscillation. On the other hand, the power from the PV panel is controlled by the maximum power point tracking (MPPT) system and kept constant $P_{PV}=P_{dc}$. By ignoring the losses in the inversion stage, the power generated by the PV panel will be equal to the average output power, $P_{o_{av}}$, as shown in Figure 4.

The time varying term will degrade the PV system performance. This ripple has a strong negative impact on the MPPT system; where MPPT is trying to track the voltage and current which result in the maximum output power from the PV panel. Having this time varying components has discussed in Table 1.

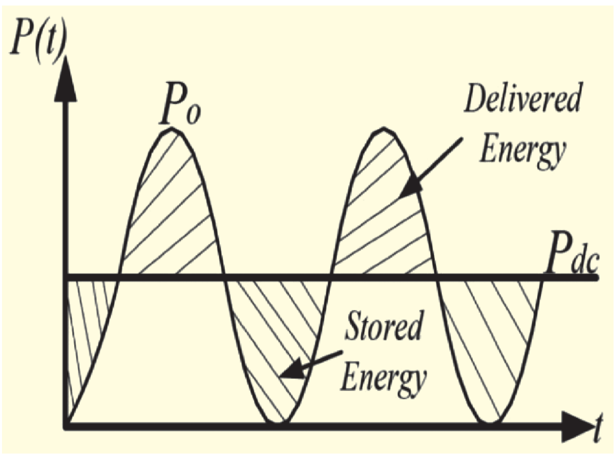

FIG. 4 THE TOTAL POWER PROCESSED BY THE DECOUPLING CAPACITOR

(voltage and current) at the PV panel will prevent from getting the maximum power and deteriorate the AC-Module's overall efficiency [7] For this reason, the pulsating power, $P_{o_{av}}$, must be handled by an energy storage device. Usually, a capacitor (Decoupling Capacitor) is used to mitigate the power ripple effect at the PV panel. This decoupling capacitor can be embedded somewhere in the inverter or it just connected in parallel with the PV panel. Figure 4 has been used in almost all commercial inverters. Even though, it is an easy technique and straight forward to be employed but it is an eminent drawback in terms of life-span.

4.0 THREE-PORT MICRO-INVERTER WITH POWER DECOUPLING CAPABILITY FOR PV SYSTEMS APPLICATIONS

The proposed three-port-topology based on the flyback type topology. Adding one switch and two diodes to the input side will allow us to move the decoupling capacitor from being in parallel with the PV panel. Where there are no constraints on the DC voltage and voltage ripple on the capacitor's terminals. The decoupling capacitor will act as a load during mode I and as a source during mode II.

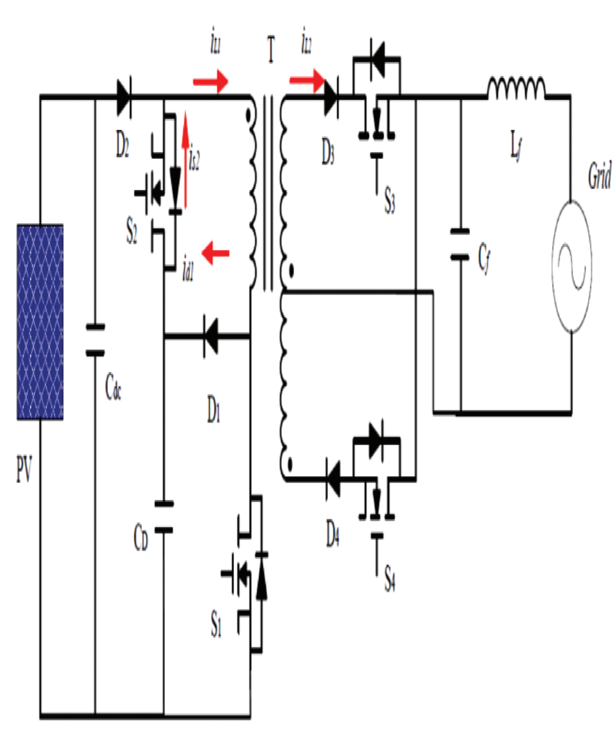

FIG. 5 THREE-PORT MICRO-INVERTER

4.1 Operation Modes

The operation of the circuit is divided into two main modes, Figure 6. Mode I: charging mode and Mode II: discharging mode. In mode I, the decoupling capacitor will be charged form the input (PV panel) through the magnetizing inductance. The amount of the stored energy is determined by how much energy is needed to be transferred into the output side. In the secondmode, this stored energy will support the PV panel to deliver the demanded power into the output side (the grid).

TABEL 1

PERFORMANCE COMPARISON OF THE VARIOUS POWER DECOUPLING TECHNIQUES

Decoupling techniques	Power rating (W)	Decoupling capacitor	Additional Cost	Efficiency	Control Complexity
Decoupling at PV side	200	7.6 mF	capacitor	η_0	No added control
	70	100 µF	Capacitor+2 switches+1 inductor	$\eta_0 - \frac{(1-\eta_d)}{2}$	Active filter control
	100	40 µF	Capacitor+1 switch +1diode	$\eta_0 - 2(1-\eta_d)$	Peak current control
	156	314 µF	Capacitor+3 switches+2 diodes	$\eta_0 - 2(1-\eta_d)$	Peak current control
Decoupling at DC- link	200	15 µF	capacitor	η_0	Low voltage loop bandwidth
	100	500 µF	capacitor	η_0	Voltage ripple estimation
High-Frequency Decoupling	100	3.3 µF	Capacitor+4 switches +1 transformer winding	---	
Decoupling at AC side	100	5.53 µF	Capacitor+2 switches	$\eta_0 - \frac{(1-\eta_d)}{2}$	Three-phase current modulation

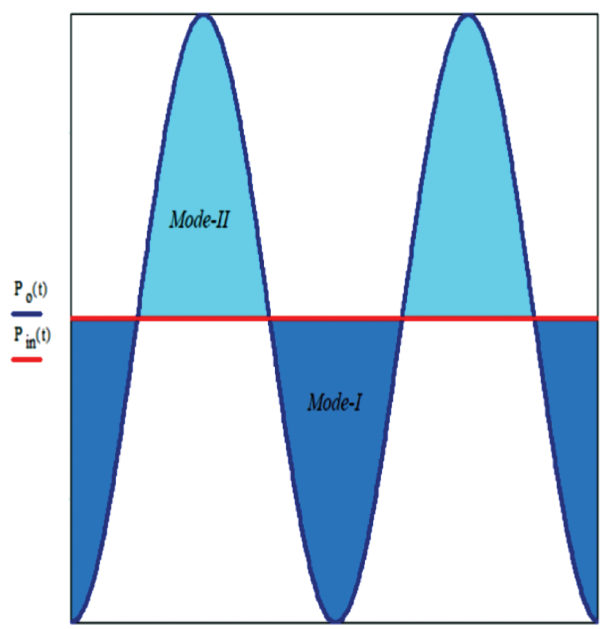

FIG. 6 INPUT AND OUTPUT POWER WAVEFORMS.

4.2 Mode-I

When the input power is greater than the output power, the circuit will operate in mode-I. The dark blue areas represent the amount of energy that will be stored in the decoupling capacitor (CD) during this mode; it will act as a load. The operation of this mode is divided into three sub-modes. First, the magnetizing inductance is storing energy from the PV panel. Then, a certain amount of this energy is stored in the decoupling capacitor. Finally, the remaining portion; which is required from the output, is transferred into output side. Figure 8 illustrates the operation of the circuit during both modes. It shows the corresponding waveforms of the magnetizing current, the input and secondary side current waveforms, and the switches' driving signal for one switching cycle in each mode.

The operation starts with sub-mode-1. S_1 is turned on and all other switches are kept off, Figure 8 (a). The PV panel is charging the magnetizing inductance. The magnetizing current is given by Figure 5.

$$i_{L_m}(t) = \frac{V_{tn}}{L_m} t \quad ....(6)$$

This peak value varies with time in order to keep the input power constant. The detailed derivation will be derived later. Once S_1 is turned off sub-mode-2 starts, where all switches are off, Figure 7. The magnetizing inductance starts charging the decoupling capacitor, C_D, from t_1 to t_2. The voltage across the magnetizing inductance is given by Figure 7.

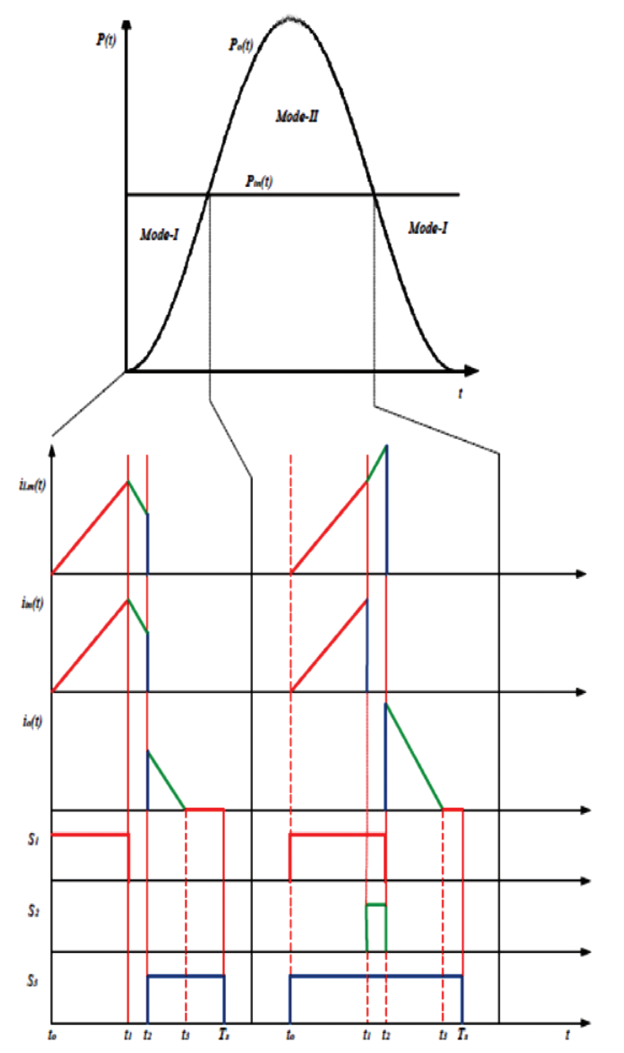

FIG. 7 INDUCTOR CURRENT, INPUT CURRENT, OUTPUT CURRENT WAVEFORMS, S1, S2, S3 GATE SIGNALS FOR THE TWO MAIN OPERATION MODES

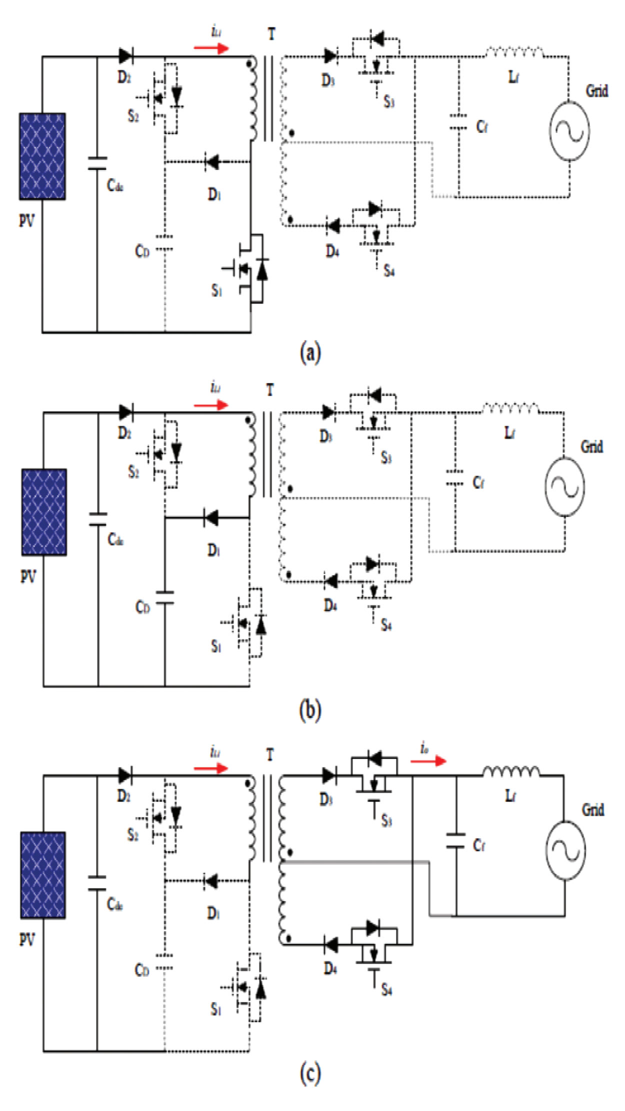

FIG. 8 OPERATION SUB-MODES DURING MODE I

And the magnetizing current is:

$$I_{L_p} = \frac{V_{in}}{L_m} D_1 T_s \quad ....(7)$$

$$L_m \frac{di_{Lm}(t)}{dt} = V_{in} - V_{C_D} \quad ....(8)$$

$$i_{Lm}(t) = \frac{V_{in} - V_{C_D}}{L_m}(t - t_1) + I_{L_P} \quad ....(9)$$

Now, after we derived the expressions of the magnetizing current during all sub-modes of mode I, we can derive the I_{LP} formula. The key point is to keep the input power constant. Since we know the value of i_{Lm} (t_2), we can derive I_{LP} using the power law as it is shown in (3.12).

$$I_{Lp} = \sqrt{(\frac{V_{in}}{V_{C_D}}(i_{L_m}(t_2))^2 - (\frac{2P_{in}T_s}{L_m})(\frac{V_{in}}{V_{C_D}} - 1))} \quad ....(10)$$

4.3 Mode-II

This mode operates when the output power is greater than the input power (supplied power) as it is shown in Figure 9. Here, the stored energy in the decoupling capacitor will subsidize the input source (PV panel) by providing the extra demanded power to the output. The decoupling capacitor will act as a secondary source during this mode. The operation of this mode also is divided into three sub-modes.

(1) Storing energy into the transformer's magnetizing inductance from the PV panel,

(2) Continue storing energy from the decoupling capacitor, and

(3) Transferring the power to the output side. These modes are illustrated in Figure 3.3.

Sub-mode-1 starts by closing S_1 while keeping S_2 off, Figure 9 (a). It is worth to mention that one of the AC side switches will be on always during mode-II as it is shown in Figure 9. Then, the magnetizing current is charged from the PV panel. It will keep charging until it reaches the peak value, I_{Lp} which is given by (3.16).

$$I_{Lp} = \sqrt{\frac{2P_{in}T_s}{l_m}} \quad ....(11)$$

Then, sub-mode-2 starts by turning on S_2 while keeping S_1 closed Figure 9. D_1 and D_2 block any current from flowing in opposite direction. Now, the magnetizing inductance is continuing charging from the decoupling capacitor until it reaches the peak value; which depends on the output voltage. The peak current value, I_{Lp2}, is given by equation 12.

$$I_{L_{p2}} = (\frac{n_2}{n_1})(\sqrt{\frac{2I_0T_s}{V_0L_2}}V_0 \sin(\omega_0 t))) \quad ....(12)$$

Finally, sub-mode-3 starts when both S_1 and S_2 are turned off, Figure 9. An exact amount of energy will be transferred into the output through either S_3 or S_4 (S (depending on the output voltage polarity)

It can be noticed from the operation modes that the leakage energy is stored in the decoupling capacitor without using any additional circuit. This is one of the advantages of the proposed topology. This leakage energy will cause a spike on the decoupling switch 2 in Figure 9 at turn off time to transfer the energy into the AC side. The modified topology in [10-12] solved this problem by storing the leakage energy in the decoupling capacitor through the flyback diodes (D_1 and D_2) in Figure 9, Three switches and two diodes are used to solve the leakage energy problem.

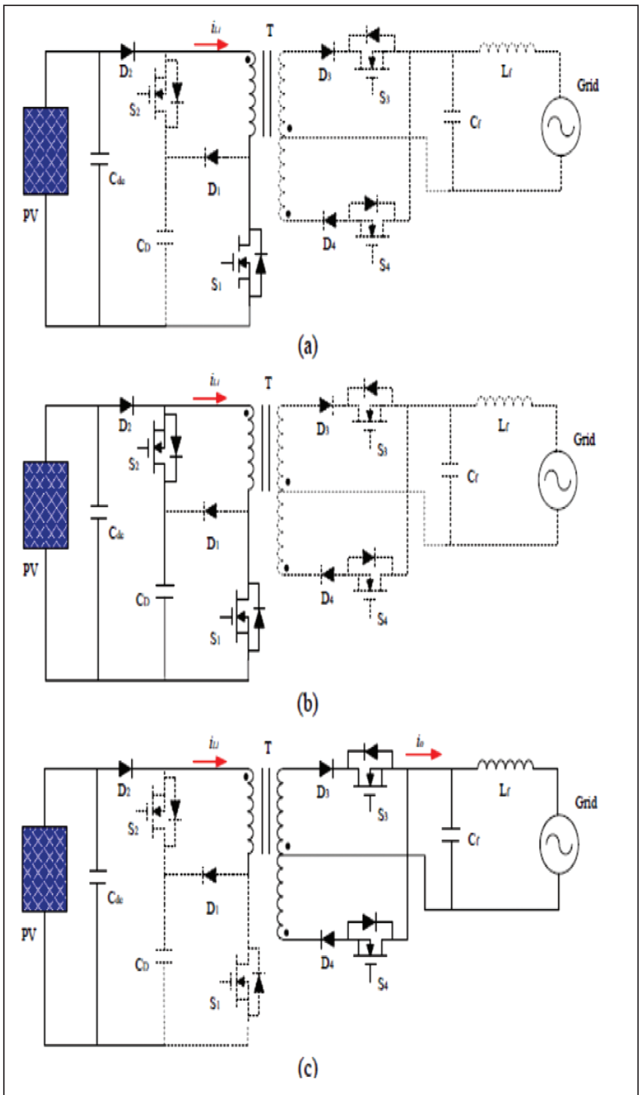

FIG. 9 OPERATION SUB-MODES DURING MODE II

5.0 CONCLUSION

The power ripple problem in single-phase micro-inverter has been studied in this paper. Different power decoupling techniques also have been presented and classified. A comparison table between these techniques was made. A new three-port topology that employs power decoupling at PV side and its complete analysis for the operation of the proposed topology have been presented. Finally, the simulation and experimental results have been shown.

The advantages of the proposed topology when compared to previous topologies may be summarized as follows:

1. No double power conversion, which results in reduced power losses.
2. The transformer leakage energy is stored in the decoupling capacitor. This means that there is no need for extra dissipative clamp circuits. Again, this will reduce the power losses.
3. Fewer components are used in the proposed decoupling circuit.

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