



Reliability Improvement of Micro-Inverter through AC-Ripples Voltage Compensator

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Abstract— In this paper the resiliency improvement of micro inverter is considered. Its life degrades mainly due to failure of DC link capacitor. The inherent 100 Hz ripples from inverter stage causes excess heat in capacitor. Consequently, the electrolyte dries out quickly and its lifespan decreases. The objective of this paper is to mitigate such AC harmonics on DC link capacitor. A compensator or active power decoupling circuit, APD, is designed in PSIM. The APD circuit is a combination of film capacitor, H-bridge and control circuit. Second frequency AC ripples are converted into DC by actively controlling the capacitor. In this manner AC harmonics are mitigated at the DC link capacitor. Firstly, a benchmark micro inverter is designed and simulated without using APD circuit. Secondly, active power decoupling is used by designing APD circuit. The simulation results show that there is a decrease in AC ripples from 9.4% to 3.2% by using series voltage compensator as compared to passive power decoupling i.e. only a bulk capacitor. The capacitor life is increased up to 19 years and hence of micro-inverter. The total harmonics distortion (THD) analysis shows that by using active power decoupling, system injects 2.7% THD as compared to passive decoupling which is 1.69%. which is still in bellow the IEEE standard of allowable 5% THD.

Keywords— Micro inverter, Reliability, Active Power Decoupling APD, PV system, AC Ripples.

I. INTRODUCTION

With the decrease in fossil fuel reserves and environmental impacts, world has got a trend to use green energy resources. These energy resources include solar energy, wind energy, micro hydro energy and fuel cell energy etc. The power plants for these green energy resources sometime produce DC power especially the solar panel which needs to be converted into AC power for connecting to grid and AC loads. Conversion to AC is required because the infrastructure already exists is AC. For this conversion we need an interface between DC power of the solar panel and the grid or AC loads. This interface is called inverter. A typical inverter is an electronic device which

converts unidirectional or direct current (DC) into alternating current or AC current. On the basis of power rating and installation, inverters have two types. One is called central inverter and second one is called micro inverter. Central inverter is connected to series string of solar panels with high voltage and power ratings of 400V-600V and above 1000W respectively [2]. On another hand micro inverter is a type of inverter with power rating of about 300W and voltage rating of 220V RMS for Asia and Europe and 120V for America and Canada. Micro inverters are connected at the back of each solar panel and feed the load or grid in parallel manner [2]. [3] Shows that micro inverter produces 3.7%, 7.8% and 12.3% more energy in case of light, moderate and heavy shading respectively, as compared to string inverter.

Most of the manufacturers of solar panels offer guarantee of 20 to 25 years of life on their solar panels. As for every panel there is a single micro inverter, and comes in embedded form in some cases, so it has to have a life span of 25 years. But in practice its life span is about 5 to 10 years and needs to be replaced which increases the cost of the system. There are many reasons for life degradation of micro inverter. One reason is the frequent failure of the DC link electrolytic Capacitor which contributes 30% to overall failures in the system [4]. The electrolyte of the capacitor wears due to temperature which is caused by the AC and DC current ripples. DC ripples comes from PV panel side due to variation in irradiance. AC ripples reflects from inverter having frequency of 100Hz. Both of these ripples increases the temperature of the capacitor and degrades its life. The aim of this thesis is to minimize the AC ripples by bypassing them through a compensator.

The main objective of this thesis is to design a voltage compensator for double line frequency AC ripples in PSIM software using active power decoupling APD techniques. First off a complete micro inverter is designed in PSIM using passive decoupling (only DC link capacitor) technique and amount of ripples on DC link capacitor are observed through wave form. Then using the noted value of ripples, life of capacitor is calculated. Secondly, active power decoupling circuit is designed in PSIM and is connected in series between converter and inverter stage and is examined to find how much ripples are

reduced on DC link capacitor. Based on these values (passive decoupling and active power decoupling), a graphical analysis is carried out which represents improvement in life of micro inverter. This paper is structured as Section II provides an overview about the background of the research, Section III presents a methodology and system description, Section IV describes the simulation results and discussion, whereas, the last section i.e. Section V portrays the conclusion of this research article.

II. BACKGROUND

Decoupling is actually the process of eliminating DC or AC ripples present in DC/AC or AC/DC power converters. In both of these converters both AC and DC ripples exist. In case of micro inverters, DC ripples come from boost converter stage and AC ripples come from inverter stage. As inverter is a bidirectional circuit it acts as a rectifier for DC link stage and inverter for grid or AC load side. That is why 2nd frequency AC (100Hz in this case) ripples come from inverter to DC link capacitor as shown in figure 1.

$$P(t) = 0.5VI + 0.5C\cos(2\omega t) \quad (1)$$

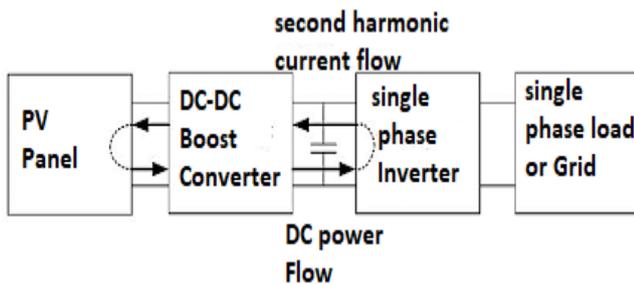


Figure 1. Second harmonics flow in micro-inverter

A. Passive Decoupling

The simplest solution to AC ripples is to use an electrolytic capacitor at DC link stage as shown in figure 1. Advantage of this type of decoupling is simplicity and cost. But the disadvantage of this decoupling technique is that it requires a large size capacitor to ensure complete elimination of AC ripples and this big size leads to thermal losses and life degradation of capacitor and hence of micro inverter [6]. [7] talks about the placement of capacitor and suggest three positions as PV side decoupling, DC side decoupling and AC side decoupling. They conclude that PV side position requires large size of capacitor as compared to DC side. On another hand if we do decoupling at AC side there will be required an additional capacitor on DC side. So if we do decoupling at DC link side, it will cover both AC and DC ripples and the complexity and cost reduces. The required size of the capacitor can be calculated by equation (2), where P_o is inverter output power, f_{line} is the system frequency (50Hz), V_{dc} is inverter input voltage and ΔV is ripple voltage [7]. David William et al in [7] mentions another passive decoupling technique which has another passive element of coupled inductor with the capacitor. In this method the series combination of capacitor and inductor is connected in parallel

with another inductor. This method has the ability that it completely directs the ripples to the capacitor with little impact on DC side. However, this method requires precise calculation of inductance values and requires magnetic circuit understanding. Equation (1) is the governing equation for second frequency harmonics reflected from AC side of inverter. Where the first term shows the DC power from converter stage and second term shows double frequency harmonics which come from AC side of the inverter. This entire research is based on the mitigation of AC ripples on DC link capacitor.

$$C = \frac{P_o}{2\pi f_{line} V_{dc} \Delta V} \quad (2)$$

B. Active Power Decoupling

In active power decoupling technique, an active element or switch such as MOSFET switch or an IGBT switch is used along with passive element as capacitor or inductor. In active power decoupling the AC ripple energy is temporarily stored in actively controlled capacitor for short time and then released to the load in next cycle. In this type of decoupling the bulk DC link capacitor is split into two small capacitors. One is placed at DC link side and accommodates DC ripples from boost converter output. The other part is controlled through switches and takes responsibility of only AC ripples. This splitting is done because as the size of capacitor increases its ESR equivalent series resistance increases, consequently thermal losses increase and its life degrades quickly [7]. So we connect a relatively small size film capacitor at DC link and other film capacitor is controlled through switches. This technique leads to different types of switching circuit, switching signal generation and topologies. According to [8] the switching circuit has two types, independent and dependent. In independent topology, the capacitor is controlled by a separate full H-bridge or half bridge circuit connected in series or parallel to DC port. For dependent technique, the inverter bridge is time multiplexed or shared with circuit of AC rippled compensator.

1). H-bridge topology

In this topology the capacitor (and inductor for smoothing out current) is controlled through H-bridge circuit as shown in figure 2, in which plus and minus terminals are connected across A and B or in series between A and P. switch S1~S4 are controlled by a reference signal which is extracted from the DC link voltage. When DC link voltage is positive, the capacitor is directed to store energy and give it back to load when voltage is negative. The advantage of this technique is that it effectively controls the energy flow with less amount of harmonics. But the limitation of this topology is that the voltage of APD port must be less than the DC port voltage [7].

2). Buck, Boost and Buck-boost based APD

The drawback of full bridge APD circuit is that it requires more components. [9] [10] and [11] propose other models based on converters, buck, boost and buck-boost. The voltage across capacitor in these circuits is unipolar. Figure 3 shows the buck converter based APD, connected across DC link capacitor, in which the ripples are compensated by capacitor through switches. The drawback of this method is that the capacitor

voltage is less than DC bus voltage, this may sometimes lead to the discontinuity of current which will contribute harmonics to the system. Other solution to AC ripples mitigation is boost converter based APD which do the same job as buck based APD, but here it gives the advantage of making the requirement of capacitor size lesser than any other topology because the voltage at capacitor is greater than DC bus voltage. The disadvantage of this method is it produces higher voltage stress on capacitor and causes safety hazards. Another solution is based on buck-boost converter topology as shown in figure 5, this APD technique allows for more reduction in capacitance requirement as compared to buck or boost converter topology because high voltage fluctuates about DC bus voltage [7]. The main limitation of this technique is discontinuity in current which injects high order harmonics in the system and degrade the efficiency.

3). Split capacitor based APD

The split capacitor APD is proposed in [12] where DC port capacitor is split into two parts. One acts as main DC filter and other part is actively controlled through switches S1 and S2 which compensate for AC ripples from inverter stage as shown in figure 6. The advantage of this method is that there is no need of extra capacitor for DC bus. This give the simplicity and makes it cost effective. Difficulty with this technique is that it requires that the values of Cr1 and Cr2 should be precisely identical. If these values are not equal, then the control system parameters will get complicated. And algorithm for controlling parameters will not easy to handle.

C. Our Proposed Design

An AC series compensator is an active filter which is connected in between DC bus and inverter which filters AC harmonics coming from inverter side to stop it from going into DC link capacitor. These ripples, if goes into DC electrolytic capacitor, degrade its life by thermally deteriorates its electrolyte. This compensator is proposed by [13] and mentioned by [7]. It consists of an H-bridge circuit and for its switching, it is controlled by a PWM (pulse width modulation) switching pattern. The benefit of this technique is that it introduces very low harmonics as compared other techniques which is a very important consideration. The drawback of this technique is complexity, more components compared to others, but its advantage is more than its limitations. This thesis also considers this technique with the innovation in circuitry in PWM switching techniques. [13] uses bipolar PWM technique which produces more harmonics as compared to unipolar PWM considered in this thesis. This thesis considers open loop control to decrease the overall complexity of the system. Active power decoupling based on series voltage compensator is shown in figure 7.

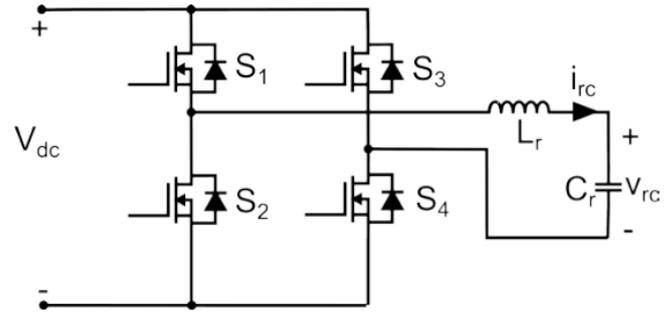


Figure 2. H-bridge topology

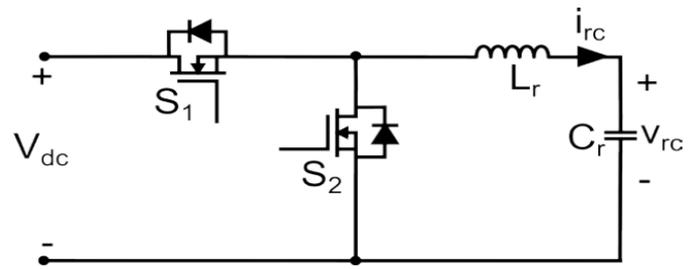


Figure 3. Buck converter based APD circuit

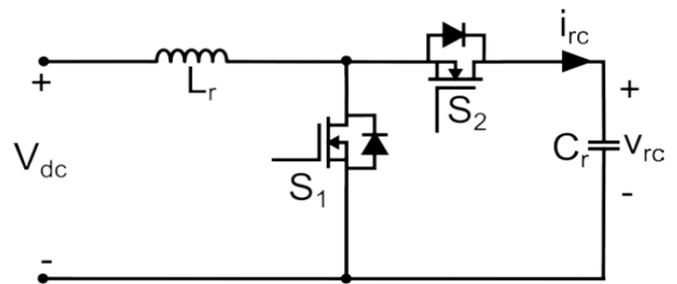


Figure 4. Boost converter based APD circuit

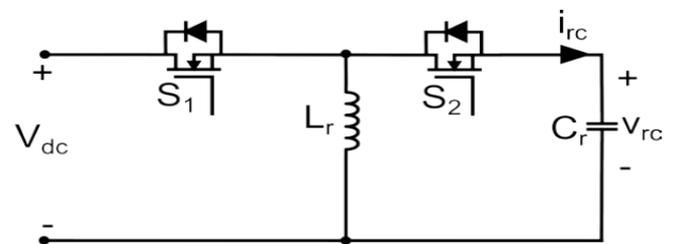


Figure 5. Buck-boost converter based APD circuit

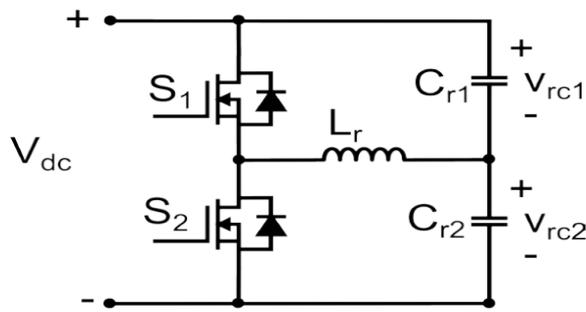


Figure 6. Split capacitor based APD circuit

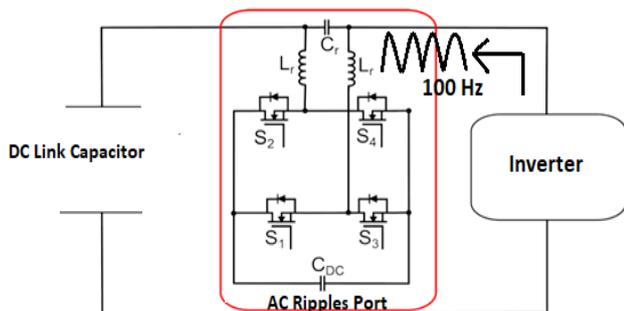


Figure 7. Series compensator based APD

III. METHODOLOGY

The reliability of micro inverter is degraded mainly due to failure of electrolytic capacitor. The capacitor burns out due to heat which is caused mainly by AC voltage ripples coming from inverter AC side. The aim of this research is to bypass these AC ripples from electrolytic capacitor. For this purpose, we design an active filter or active power decoupling circuit abbreviated as APD which is actively operated through switches. First of all, a specific power and voltage rating for micro inverter is considered. Before designing, all parameters are calculated through formulas. For this project a PV module of 300 watts of power and 40 volts is considered. The designing of micro inverter is done in PSIM software starting from boost converter. The capacitance and inductance values of boost converter are calculated by using equation (3) and (4). The switching frequency of the MOSFET is 20k Hz and duty is found from equation 5 using desired values of input and output voltages. The inverter stage is made up of four IGBT switches which are operated by SPWM circuit based on unipolar SPWM which is

three level modulation scheme and using switching frequency of 20k Hz. For pure sine wave at the output an AC filter is used whose values of inductance and capacitance are calculated using equation (6) and (7) respectively. In first case for power decoupling, a simple capacitor is used and the circuit is simulated. Based on the capacitance of decoupling capacitor, the magnitude of AC ripples is measured as benchmark value from the graph of voltage at DC link bus. After this active power decoupling APD circuit is designed for compensation of AC ripples which is main objective of this thesis. This circuit consists of H-bridge, capacitor and filters. After designing series compensator, it is connected in series between the inverter stage and DC link capacitor. The circuit is simulated again and the AC ripple voltage at DC bus is measured. Now the measured AC ripple voltage is very less than the benchmark value. Based on mitigated voltage value, life of capacitor and hence life of micro inverter is calculated and is graphically represented. Methodology of the research is shown in figure 8 through a flow chart and complete simulation circuit in figure 9. The circuitry of series active power decoupling circuit consists of differentiator, unipolar sinusoidal pulse width modulator SPWM circuit and H-bridge circuit. Differentiator sense the voltage at DC bus having a signal consists of DC voltage and second harmonic frequency voltage. Differentiator extracts the 100 Hz AC component and gives it to SPWM generator as reference voltage wave. SPWM generator compares this reference wave with 20k Hz triangular wave and generates switching patterns. This switching signal is given to H-bridge circuit connected in series to DC bus. The H-bridge is controlled through switching in such a way that it converts 100 Hz AC ripple signal to a DC signal because the H-bridge in this case is bidirectional, it acts like a full wave rectifier circuit operated in reverse directional. The output of H-bridge is a pure DC voltage (in ideal condition, but it still have some small amount of AC ripples) which is added to DC bus. DC link capacitor in this way is protected from AC ripples.

$$L = \frac{d(1-d)^2 RT_s}{\%ripples} \quad (3)$$

$$C = \frac{dT_s}{R\%ripples} \quad (4)$$

$$d = 1 - \frac{V_{in}}{V_o} \quad (5)$$

$$L = \frac{V_{dc}}{8 \Delta ripples f_{sw}} \quad (6)$$

$$C = \frac{\phi P_{rt}}{2\pi f_{line} V^2} \quad (7)$$

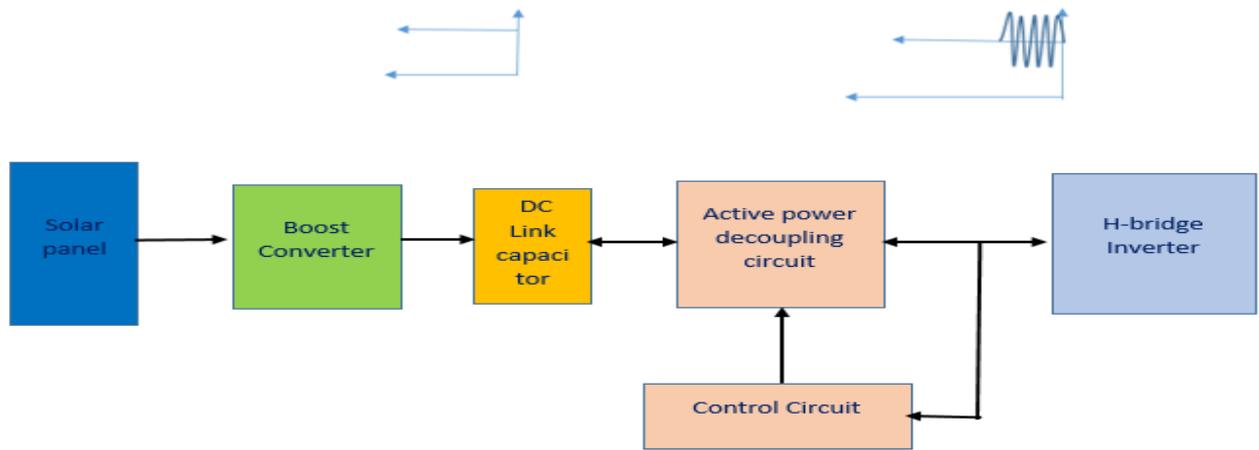


Figure 8. Flow diagram for series compensator

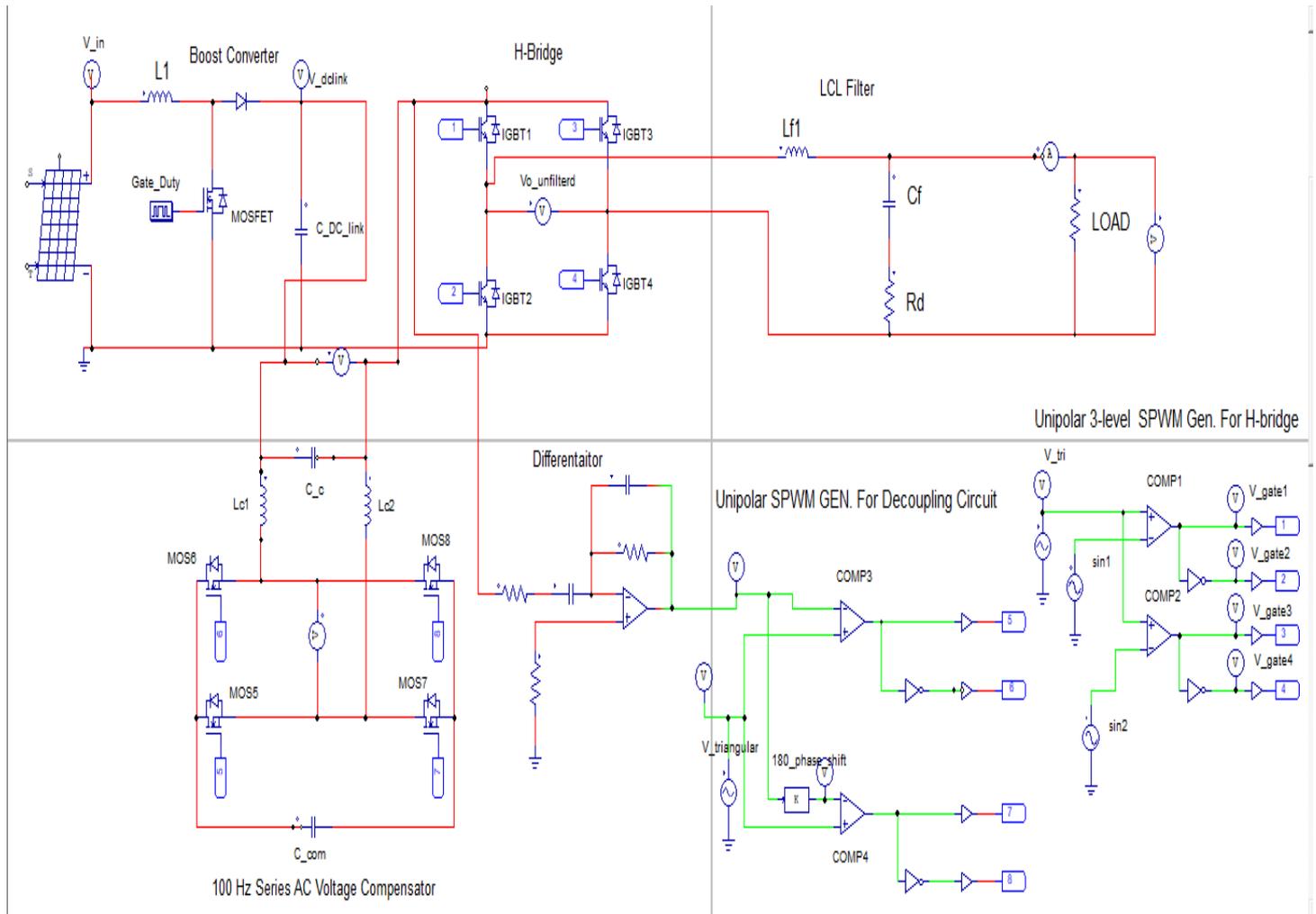


Figure 9. Complete circuit diagram of micro-inverter with APD circuit in PSIM

IV. RESULTS AND DISCUSSION

The life span of an electrolytic capacitor is effected due to external and internal environmental factor. External factor maybe ambient temperature, humidity, pressure, and vibration. The impact of external factor on life of electrolytic capacitor is minimum and can be neglected. But internal factors have significant impact on life of capacitor. These factors include operating voltage, charging and discharging and the more important one is the ripple current through the capacitor [7]. The equivalent series resistance(ESR) of electrolytic capacitor is relatively higher than other type of capacitor. Due to this, when ripple current passes through capacitor, it causes heat dissipation inside capacitor which is shown by equation (8).

$$H = I_{rip}^2 \times ESR \quad (8)$$

Equation (8) shows that for constant value of ESR, heat generated inside the capacitor is proportional to the square of ripple current. This shows a significant contribution to inside temperature of electrolytic capacitor by the ripple current. This temperature rise (ΔT) can be approximated by equation (9).

$$\Delta T = \frac{I_{rip}^2 \times ESR}{\beta A} \quad (9)$$

Where, I_{rip} is ripple current ESR is equivalent series resistance β is heat radiation factor and A is surface area. Electrolytic capacitor is an electro-chemical device. Due to high temperature, the rate of chemical reactions inside it increases which ultimately degrade life of capacitor. In [7] this life degradation due to ripples and operating voltage can be calculated by using Arrhenius law in equation (10).

$$L = L_o * 2^{0.1(T_m - T_a)} * M_v * 2^{\frac{\Delta T_r - \Delta T}{\Delta T_r}} \quad (10)$$

Where ΔT is temperature developed due to ripples ΔT_r is rated ripple temperature L is expected life and L_o is base life calculated by manufacturer. T_m is maximum allowable temperature, T_a is actual operating temperature. M_v is voltage multiplier and is given by equation (11).

$$M_v = 4.3 - 3.3 \frac{V_a}{V_r} \quad (11)$$

V_r is rated voltage and V_a is the applied voltage. The value of M_v is 1 when capacitor is operated at rated DC voltage and greater than 1 when it is operated at less than rated DC voltage. Now using PSIM we simulate two systems to show their life span due to AC ripples.

A. Ripples on DC bus in Benchmark Micro inverter.

In this benchmark micro inverter system, the circuit is simulated in PSIM without using series AC voltage compensator. The peak to peak voltage ripples in this system were 28V as shown in figure 10. In the circuit for this benchmark system, only an electrolytic capacitor of 400uF capacitance is used to decouple the DC voltage variations. Voltage at the DC link bus consists of two components, one component is 310V DC voltage comes from boost converter and along with it another voltage component which is 100Hz AC ripples come from inverter side.

B. Ripples in Proposed Micro inverter.

In the proposed micro inverter whose schematics is given in figure 9, an h-bridge is controlling the charging and discharging of capacitor C_{com} . This h-bridge is controlled by SPWM generator circuit. This h-bridge is actually works in opposite manner (converts AC ripples to DC voltage) as compared to inverter h-bridge which converts DC into AC voltage. the wave form of this proposed micro inverter is shown in figure 11. This shows that AC ripples in proposed system are 3.6V peak to peak which is considerable reduction as compared to benchmark system which are 28V peak to peak. These results shows that ripples in benchmark system are 9% but in proposed system it is 1.1%. which is a reasonable reduction achieved by the proposed system. For IEEE standard the allowable ripples are 5%. Then using equation (10) the capacitor life graphs for benchmark micro inverter and proposed micro inverter is plotted in figure 12. Expected life of capacitor for different decoupling techniques are summarized in comparison table 1. Although a lillte complex but the our proposed design enhance life expectancy of the capacitor.

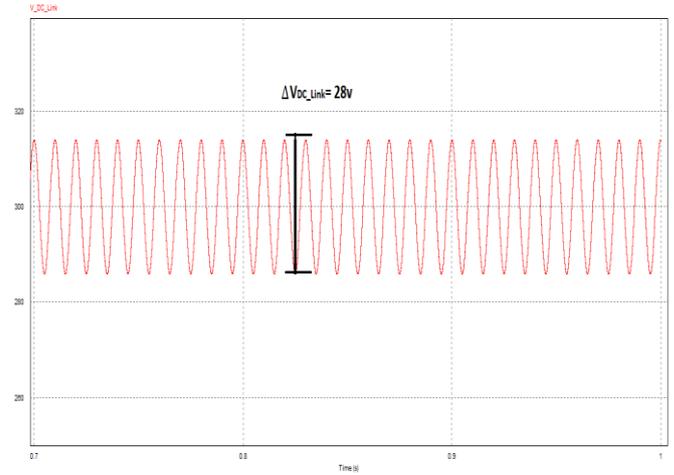


Figure 10. AC Ripples On DC Bus In Benchmark System

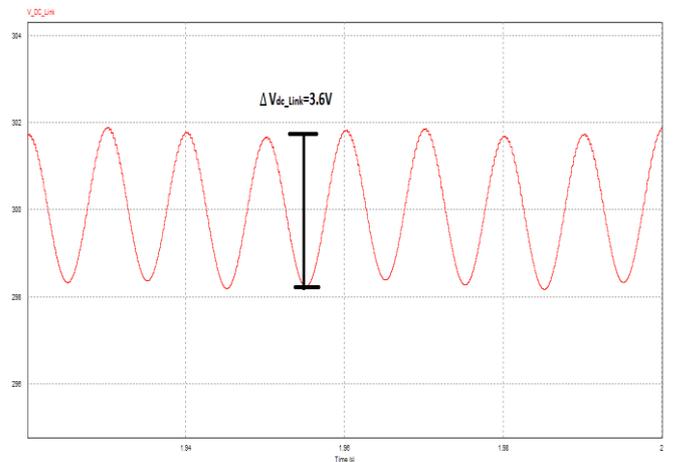


Figure 11. Ripples on DC link Capacitor in Proposed Micro inverter

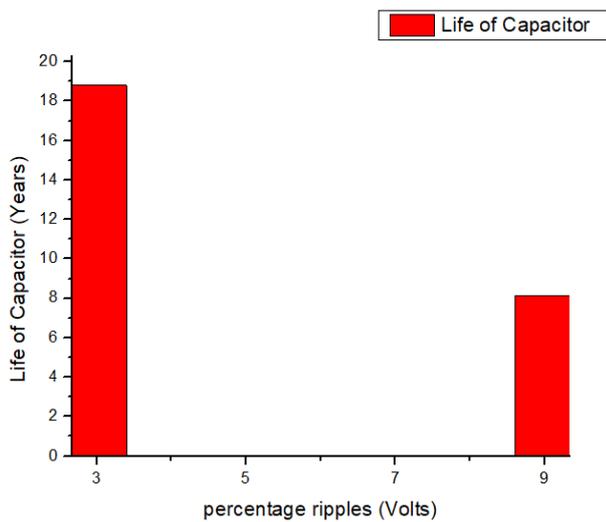


Figure 12. Capacitor Life Graphs Proposed (left) Benchmark(right)

TABLE I. CAPACITOR LIFE COMPARISON

S No	Reference	Decoupling technique	%age Ripples	Capacitor Life(years)
1	Haibing et al	PV side passive decoupling with no ripples compensation on DC link side.	31 %	1.5 yr.
2	Our benchmark	Small capacitor	9%	6 yrs.
3	R. Wang et al	Buck-boost based APD	4.4 %	11 yrs.
4	Y. Tang et al	Half bridge APD	3.2 %	12 yrs.
5	Our proposed design	H-bridge unipolar SPWM based APD	1.1 %	19 yrs.

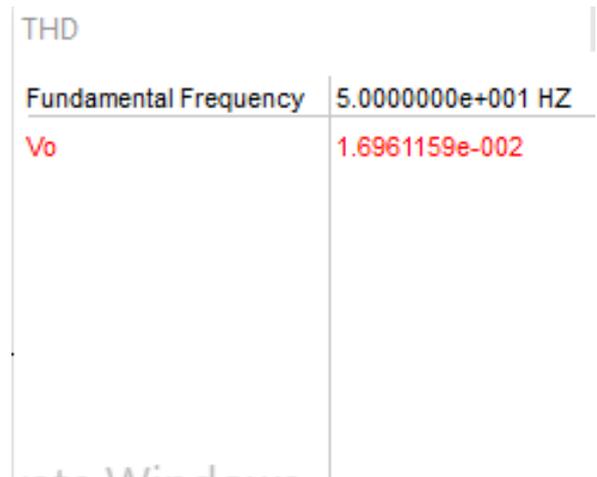


Figure 13. THD without compensator

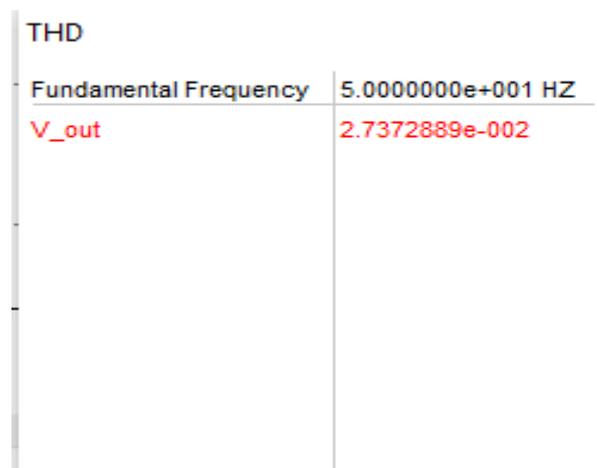


Figure 14. THD with Compensator

C.Total Harmonics Distortion THD

The allowable amount of total harmonics distortion THD by IEEE is 5%. Figure 13 shows the simulation results for total harmonics distortion for micro inverter system with only capacitor as decoupling element which are only 1.7% and figure 14 shows result for THD when active power decoupling circuit is inserted along with DC link capacitor which increases the distortion only up to 2.7% which is still very less than the IEEE standard. Table 1. Capacitor life comparison.

CONCUSLION

Solar energy is one the renewable energies which is available in abundance but to harvest it requires a system of PV modules. Like many other renewable sources e.g. fuel cell, micro hydro and small wind generator, PV module generates a DC power. This DC power is need to be converted into AC power as more than 95% of loads and generators already installed produces or consume AC power. For this conversion we need an electronic device called inverter which converts unidirectional or DC current to alternating or AC current. On the bases of power rating and configuration inverters can be a central or conventional inverter which is connected to a series string of PV modules and it can be of small rating called micro inverter. Micro inverter has about 300 Watts of rating and connected at the back of each and every PV module and all of them are connected to a common bus. In certain small scale application such as residential, small industries, labs, electric car etc. micro inverters outperform central inverters. In such cases a match between life of micro inverter and PV module is necessary to reduce maintenance cost. As most of the PV manufacturers offer

20 to 25 years of guarantee on their modules, so it is necessary for micro inverter to have a life of 20 to 25 years. But in practice it is not the case as it has hardly a life span of 5 to 10 years. The reason for its short life is electrolytic capacitor, connected at DC link for power decoupling, burns due heat which is caused by AC ripples coming from inverter side. This thesis mainly focused how to mitigate these ripples by using another film, long life capacitor actively controlled by an h-bridge circuit which converts AC ripples into DC voltage at the DC link bus. For this purpose, this thesis developed an active power decoupling ADP circuit which is connected in series between boost converter and inverter stage. This research work develops the model in PSIM environment. Two model of micro inverters has been simulated one is a benchmark system without ADP series compensator which gives 28V peak to peak ripples at DC link capacitor. And other system is proposed micro inverter with series compensator which gives 3.6V ripples at DC link capacitor. Using Arrhenius equation, the life graphs of capacitor for both system has plotted which shows that reducing ripples from 9% to 3.6%, increases life from 8.16 year to 18.8 years.

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