A Review on Non-Isolated Inductor Coupled DC-DC Converter for Photovoltaic Grid-Connected Applications

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Abstract- In the present trend, the usage of photovoltaic power generation keeps on increasing due to non-availability of nonrenewable sources. Nowadays, the generation of solar power is increasing, but the efficiency of Photovoltaic (PV) is less. Generally conventional boost converters are used to increase the voltage of PV, but it's not widely used due to its high duty ratio, increased voltage stress, switching losses and increased cost of converter. To overcome all the above drawbacks and to improve the system efficiency, different types of inductor coupled dc-dc converters have been considered and merits and demerits of all the type of dc-dc converter is listed in this paper. Among all dc-dc converters, the capacitor clamp inductor coupled dc-dc converter is preferred by most of researchers to improve the overall system performance and reduce the cost of the converter.

Keywords: DC-DC converters, Efficiency, Inductor coupled, Photovoltaic module, Reverse recovery.

1. Introduction

The world's energy usage is growing due to the increase usage of electrical appliances. There are two types of energy sources, conventional and non-conventional energy sources. Conventional (non renewable) energy sources are limited in their availability. Nonconventional (renewable) energy sources are available naturally in excess [1], [83]. Renewable energy sources are eco-friendly; require less maintenance, life time energy generation and reliable source of energy. The renewable energy sources are wind, solar, biomass, ocean, geothermal [2], [89]. Recent power scenario of India is shown in the Fig.1. In India the net electricity generation is 263.66GW. The renewable electricity generation capacity is about 34.35GW and requires 13% of entire installation as on March 2015.

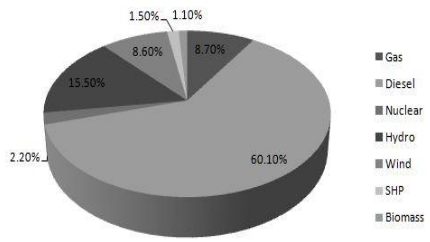

Fig.1. Power Generation Scenario of India [2]

In India, the global renewable energy installation data is shown in Fig.2. Here, world non-conventional installation capacity is 673GW, in which solar energy installed capacity is about 177GW [3]. India's solar installation capacity as on March 2015 is about 3.3GW. The country wise solar power installation capacity is shown in Fig.3.

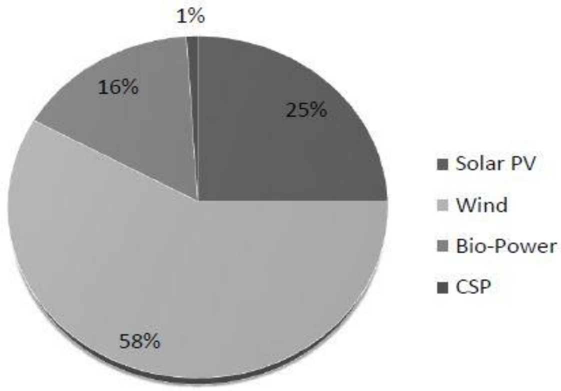

Fig.2. Gobal renewable statics [3]

It is commonly observed that the PV power generation keeps on increasing [4]. The photovoltaic power is used in batteries, fuel cell, hybrid electric vehicles, auto motive, head lamps, water pumping etc [82], [86]. The main feature of PV system is it requires less maintenance. There is no existence of moving parts. As a result, no noise pollution takes place [5].

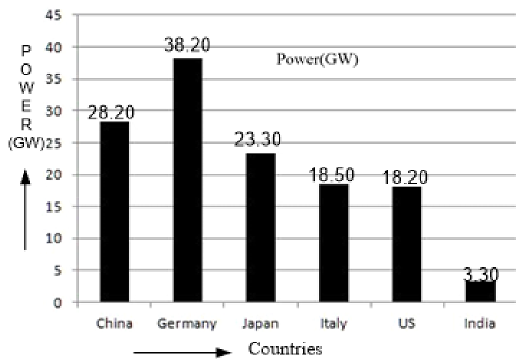

Fig.3. Country wise solar installation [4]

The interfacing of the dc energy sources with converter is one of the challenging tasks in photovoltaic power generation [82]. The photovoltaic power is used mostly in residential applications and it is a quick rising section due to the lack of firewood power and ecological pollution [6].

To get high efficiency of the solar energy generation, it's essential to maintain balance between PV generation and load, so that the operating point of PV generation coincides with the maximum power point (MPPT) [7]. However, the MPPT varies time to time due to the irradiance of sun light, and hence, it varies circuit parameters. The photovoltaic generator shows a non-linear characteristic due to solar irradiations [8]. The main problem of PV is high installation cost per KW, and less efficiency. The PV-power production exhibits non linear V-I characteristics. In general when solar cells are connected in series it gives higher amount of voltage whereas, solar cells connected in parallel gives more current. So, the combination of series and parallel for different PV cell preferred to set required value of voltage and current [9], [88], [94]. The layout of PV power generation to the grid is shown in Fig.4.

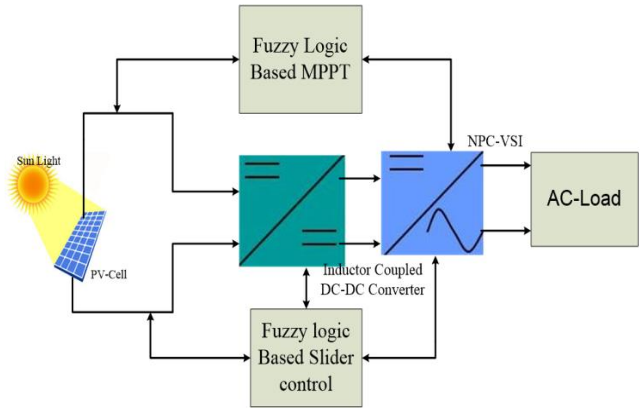

Fig.4. Basic schematic of solar power generation

The most significant trouble occurs after the irradiance level of solar module happens to be sensitive and it varies from one cell to another cell, and the Individual cells disturbance can be overcome by using different types of coupled inductor dc-dc converters and MPPT techniques. The global expected photovoltaic installation expected capacity up to 2020 is shown in Fig.5 [10].

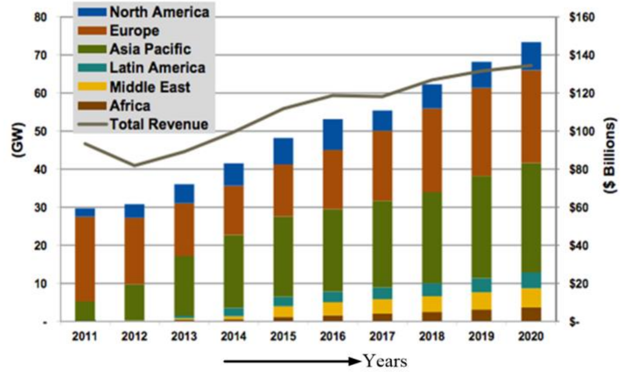

Fig.5. Basic statics of solar power installation [12]

This paper is organized as follows the classification of dc-dc converters highlighted in section 2. Section 3, deals with mathematical modeling of solar cell. Section 4 presents the design of coupled inductor for improving voltage gain in dc-dc converters and finally section 5, deals with the different types of non-isolated dc-dc converters.

2. Classification of DC-DC Converters

Basically, a single stage central inverter directly connected to PV for converting DC to AC. Due to direct connection with PV, the cost of system decreases and also the transmission losses decreased which in turn increase the efficiency. From the basic survey, PV-connected inverters have good performance; efficiency and power factor exceed 0.91 for wide operations while the total harmonic distortion is less than 5% [11]. But this type of connection reduces the PV utilization factor. The reduction of power in PV-panel is due to partial shading which is eliminated by using interleaved boost converter or electrical array reconfiguration, instead of single stage inter leaved boost converter [12].

There are two types of dc-dc converters: isolated and non-isolated dc-dc converters [12]. Both converters operate at high frequency, but the main difference is, non isolated converters do not have transformer and no need of additional rectifier. Because of that reason non-isolated converters consist of fewer components, size of the converter and losses are less. TDKLMBDA I6A dc-dc converter model used for 24V, 250W application and it gives efficiency 98% at high temperature without heat sink. The main cause for choosing non-isolated dc-dc converter is cheaper compare to isolated converters, cost saving up to 50% [13].

2.1. Non-isolated dc-dc converters

Majority of dc-dc converters are non-isolate type, those are buck, boost, buck-boost, CUK and SEPIC converters. Buck converter is a forward mode type dc converter. Buck converter output voltage can be controlled by varying duty cycle. Buck converter output voltage is less than the input voltage. So buck converter is also known as step down chopper. Most of the dc-dc converters use power MOSFET’s (Metal Oxide Semiconductor Field Effect Transistors) for high speed switching operation. MOSFET is a majority carrier voltage controlled device, no need of injection minority carriers and it is superior to the BJTS for high switching frequency and high voltage, current applications [14]. These converters are finding applications is battery operated vehicle and DC power supply [15]. The main advantage of buck converter deals with one switch and achieves efficiency 90%. Draw backs of these converters are slow transient response and high output current ripple. Boost converter is used to converting low level dc to high level dc voltage. Boost converters are used to step up the battery voltage and power amplification [16]-[17]. Buck-Boost converter output voltage is less than or greater than the input voltage and it is used as a self regulated power supply [18], [84]. CUK converter operation is similar to buck-boost but the energy storage element is capacitor, whereas, in buck-boost converter the energy storage element is inductor [19]. The Single Ended Primary Inductor Converter (SEPIC) is the same as buck-boost converter but the difference is polarity of output voltage [20]. In all dc-dc converters, an additional sub circuit Resistor Capacitor Diode (RCD) is used to reduce the energy stress across the switch but losses are additional and hence degrade the efficiency. The active clamp fly back converters recover the leakage energy and minimize the electrical energy pressure, but losses are same as RCD [21], [96]. In dc-dc converter the electrical energy gain can be controlled by using different switching devices, MOSFET’S, IGBT, BJT, TRIAC etc [22]. So, the selection of switches for dc-dc converts operation is an important criteria. Based on voltage and current requirement the switches are selected and it is shown in table.1.

Table: 1. Parameter comparison of switches [27]

Parameters	***BJT***	***MOSFET***	***IGBT***
Switch Speed	Moderate	High	Moderate
Control parameter	Current	Voltage	Voltage
Circuit design	high complexity	Easy	high complex
Robustness	High	Less	Less
Power consumption	More	Less	More
Power dissipation	High	Less	Medium
Power control	Low	High	Moderate
Operating voltage	More	Less	Medium
Gate to source voltage	Less	High	High
Input impedance	Low	High	High
Driver circuit complexity	More	Less	Less
Parallel operation	Difficult	Easy	Easy
Temp sensitivity	More	Less	Less
Operating temp	150^0C	200^0C	>200^0C
Operating characteristics	Non-linear	Linear	Moderate
Switch on resistance	Low	High	High
Trans conductance	High	Low	Low
Switching frequency	Low	Very high	High
Maximum voltage rating	1.5kV	1kV	3.5kV

From the above parameter comparison of switches, MOSFET is a suitable device for all non-isolated inductor coupled dc-dc converters. In boost converter over voltage flow controlled by the use MOSFET’S.

2.2. Isolated dc-dc converters

An isolated dc-dc converter consists of electrical barrier between input and output. High frequency transformer is used as a barrier. Due to this barrier, the converter is protected from high input dc voltages. The interfacing and improving efficiency of dc-dc-dc converter is a major concern in power system operation. There are different types of inductor coupled dc-dc converters have been discussed for improving overall power system efficiency [23]-[24]. The cost and complexity of isolated converter is more compared to non-isolated converters. So, non-isolated dc-dc converters are mostly preferred.

2.3. Summary of isolated and non-isolated dc-dc converters

Non-isolated dc-dc converters are more common in electrical heating. LM117 three terminal voltage controllers are used in non-isolated dc-dc converter. In that, one input is uncontrolled, second one controlled and third input is ground. The cost of converter, size is less, this is one of the basic and foremost advantages in this topology and its design is easy. These converters mostly used in negative ground application in hybrid electric vehicles and dc power appliances. The main disadvantage in non-isolated dc-dc converter is high input dc voltages applied on switches. Hence, the switches failed permanently. So, non-isolated dc-dc converters are used for medium voltage applications [24].The input and output of isolated dc-dc converters are not electrically coupled. Hence, the converter switches protected from high input voltages. Isolated converters are used for positive, negative and floating grounding equipment from information come to telecommunication.

2.3.1. Finding of isolated and non-isolated dc-dc converters

Select multi-meter or ohm meter to calculate the resistance between the common terminals of output and input of dc-dc converters. If the terminals are shorted, it is a non-isolated dc-dc converter otherwise; it is an isolated dc-dc converter.

3. Mathematical Modeling Of PV-Cell

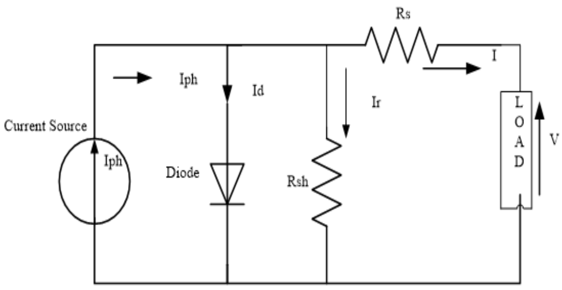

Fig.6. Basic single diode PV-module [25], [82]

The photovoltaic cell operation is analyzed by the use of Single diode equivalent circuit and it's shown in Fig.6 [95]. The I-V characteristic of PV is explained by the use of superposition of dark and sunlight current. Due to illumination of sunlight I-V characteristics shifts from first to fourth quadrant. Fig.6 is used together with the following set of equations to explain the I-V characteristics of PV cell or module or array [25], [90] and the PV panel parameters are defined in Table 2.

$$I = I_{ph} - I_d - I_r \tag{1}$$

$$I_{ph} = I_{sc} + K_i * \left(T_{op} - T_{ref}\right) * S \tag{2}$$

$$I_{rs} = \frac{I_{sc}}{\exp(M - 1)} \tag{3}$$

$$M = \frac{q * V_{oc}}{N_S * A * K * T_{op}} \tag{4}$$

$$I_0 = I_{rs} * \left(\frac{T_{op}}{T_{ref}}\right)^3 * \exp\left[\left(\frac{q * E_g * N_S}{K * A}\right) * a\right] \tag{5}$$

$$a = \left(\frac{1}{T_{op}} - \frac{1}{T_{ref}}\right) \tag{6}$$

$$I = N_p * I_{ph} - N_p * I_o\left[\exp(B * C) - 1\right] \tag{7}$$

$$B = \frac{q}{N_S * A * K} \tag{8}$$

$$C = \left(V + I \ * R_S\right) \tag{9}$$

The single diode equivalent circuit determines the I-V curve, as a function of operating temperature and sunlight irradiations [97]. Power generated by the PV array varies with solar irradiations and temperature, and hence these parameters affect the I-V characteristics of the solar panels [84]. The effect of irradiations and temperature on I-V and P-V characteristic of PV array is shown in Fig.7 and 8. From the different temperature coefficients, the PV cell efficiency is calculated as, [26],

$$\eta = \eta_r\left[1 - \beta\left(T_c - T_r\right) + \gamma \log \phi\right] \tag{10}$$

An additional formulation has been used to calculate the efficiency which is linearly dependent on temperature,

$$\eta = \eta_r - \mu(T_c - T_r) \tag{11}$$

The temperature of the PV cell is calculated as [30],

$$T_c = T_a + \left(NOCT - 20^0 C\right) * \frac{S}{180} \tag{12}$$

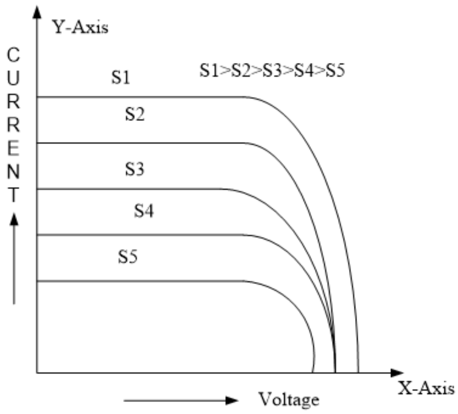

Fig.7. I-V characteristics of PV-array at different irradiations, [34], [92]

The PV modules observe the sun light energy in the form of irradiance and it is given by,

$$E_{pv} = \alpha\tau\phi \quad (13)$$

There are two types energy loss in PV cell. The losses formed in PV due to the electrical conduction is equal to,

$$E_{loss} = \eta\phi \quad (14)$$

Table. 2. Parameters of basic single diode PV-module [32]

Symbols	***Meaning***	***Units***
I_{ph}	Photon current	A
I_{rs}	Reverse saturation current	A
I_o	Saturation current of PV	A
I	PV module output current	A
I_{sc}	Short circuit current of PV	A
K_i	Temperature co-efficient	-
T_{op} (or) T_a	Operating temperature	Kelvin
T_{ref} (or) T_r	Reference temperature	Kelvin
Q	Electrical charge($1.6*10^{-19}$)	Colum
S or ϕ	Irradiations	W/cm^2
N_s	Number of series cells	-
E_g	Band gap energy(1.12)	-
K	Boltzmann constant($1.3805*10^{-23}$)	J/K
A	Ideality factor(1.6)	-
N_p	Number of parallel cells	-
R_s	Series resistance	Ohm
V	Output of PV module Voltage	V
η	Efficiency of PV module	-
η_r	PV module reference efficiency	-
α, β,μ	Temperature co efficient	$^0C^{-1}$
K	Diode emission factor	-
FF	Form factor	-
I_{do}	Diode reverse current	A
NOCT	Normal operating cell temperature	$^0C^{-1}$

The collector to surroundings thermal losses is calculated as:

$$U_{pv} * (T_c - T_a) \quad (15)$$

From equation (13), (14), (15), the energy balance equation is calculated as,

$$\alpha\tau\phi = \eta\phi + U_{pv} * (T_c - T_a) \quad (16)$$

From equation (11), (12), the PV unit heat is premeditated as,

$$T_c = \left\{ \frac{U_{pv} * T_a + \phi[\alpha T - \eta_r - \beta * \eta_r * T_r]}{U_{pv} - \beta * \eta_r * \phi} \right\} \quad (17)$$

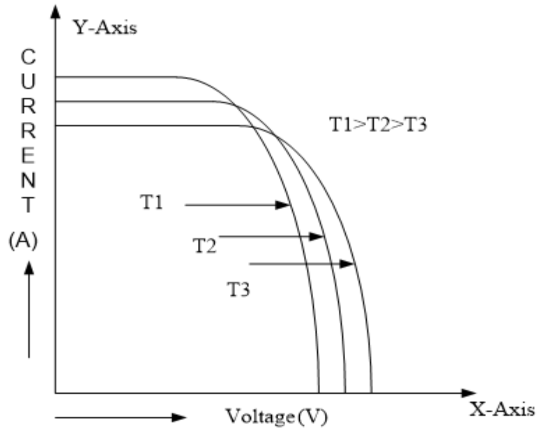

Fig.8. I-V characteristics of PV-array at different temperatures [34]

From equation (11), (13), the cell temperature is,

$$T_c = \left\{ \frac{U_{pv} * T_a + \phi[\alpha T - \eta_r - \beta\eta_r * T_r]}{U_{pv} - \phi\mu} \right\} \quad (18)$$

The solar panel consists of N_s series and N_p parallel cells. The array voltage is calculated as, [28], [84]

$$V_A = -I_A * R_s \left(\frac{N_s}{N_p}\right) + \left(\frac{N_s}{\wedge}\right) * \log(X) \quad (19)$$

$$\wedge = \frac{q}{A * K * T_{op}} \quad (20)$$

$$X = \left(1 + \frac{N_p I_{ph} - I_A}{N_p * I_0}\right) \quad (21)$$

$$E_g = m(1.16 - 7.02 * 10^{-4} \frac{T^2}{T - 1108}) \quad (22)$$

In the next section, the different types of inductor coupled dc-dc converter for PV grid connected application is presented. Non-isolated converter uses coupled inductor to increase voltage gain [98-99]. But the leakage inductance of the coupled inductor induces voltage stress on switches. And hence the converter efficiency decreases. Here, the capacitor clamp inductor coupled dc-dc converter is used to get better performance compared to all of the converters [29], [101-102].

4. Design Of Coupled Inductor For Voltage Booster

Coupled inductor technique is an upcoming technique to step up the voltage for digital signal processing, central processing unit (CPU), dc-dc converter necessities which are intended for achieving good steady state and transient performance [30]. The dc-dc converter voltage gain improves the use of coupled inductor without increasing duty cycle [31], [32]. The basic coupled inductor operation is shown in Fig 9.

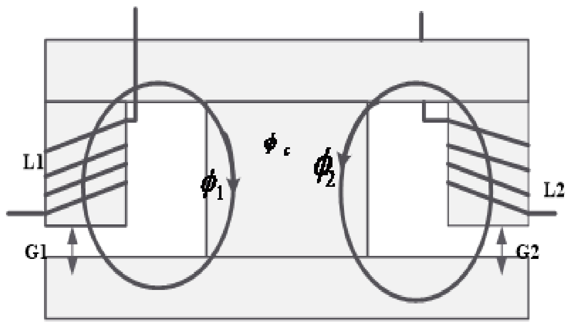

Fig.9. Core design of the integrated inductors [30]

Automotive use of multiphase coupled inductor consists of four coupled inductors which is functional for four segment interleaved 1KW bidirectional 14V to 42V dc-dc converter. Coupled inductor minimizes the circuit structure and optimizes the faster transient response for medium voltage applications of two and four wheeler vehicles [33], [34]. The two windings build on the two external legs of the core. Space break is necessary on every external leg to stay away from dispersion of the core. Commercially no space gap is provided on the middle leg, so that both inductors can be decoupled. The magnetic flux swell decreases in the middle leg because of that core loss decreases and efficiency increases. Core structure is used in order to reduce the magnetic swell in the middle leg and hence to set improved efficiency, it is the best practice to use the core structure, which consists of air gap in three legs. Though, this type of attractive core is not a standard manufacturing practice [35], [36].

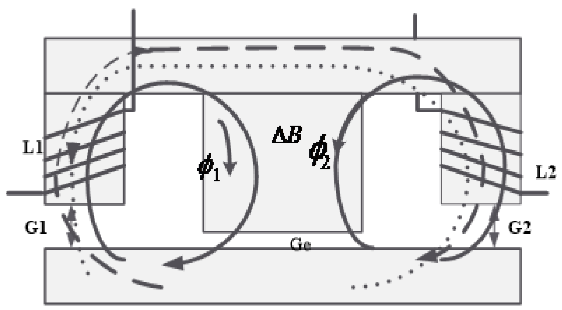

Fig.10. Advanced core configuration of the integrated inductors [30]

The difference between this Figures 9, 10 determines air gap between the legs. Fig 9, the air gap between the three legs is less and a result is low reluctance. Due to this better static and dynamic performance can be achieved. The air gap takes place between two legs does not affect the mechanical stability of cores [37], [38].

In this core structure, the middle leg is no longer a less reluctance path for the fluxes because of the air gap. If the second winding L_2 is gets open circuited, the flux produced by the primary winding goes to three legs. Similarly, when the primary winding L_1 gets open circuited secondary winding flux goes through the three windings. Based on the direction, current inductors are coupled directly and inversely. Here, the direct and indirect coupling is shown in the Fig.11. Mutual inductance is more in direct coupling, and it is less in reverse coupling [39], [40]. For inductor coupled buck converter the output wave forms is shown in Fig, 12, L_1 and L_2 are primary and secondary winding inductances. M is the mutual inductance.

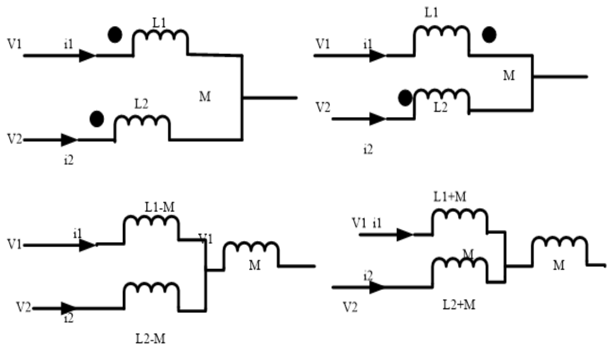

Fig.11. Direct and indirect coupling of inductors [30]

Direct coupling voltages are calculated as,

$$V_1 = L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \tag{23}$$

$$V_2 = M \frac{di_1}{dt} + L_2 \frac{di_2}{dt} \tag{24}$$

Similarly, indirect coupling voltages,

$$V_1 = L_1 \frac{di_1}{dt} - M \frac{di_2}{dt} \tag{25}$$

$$V_2 = -M \frac{di_1}{dt} + L_2 \frac{di_2}{dt} \tag{26}$$

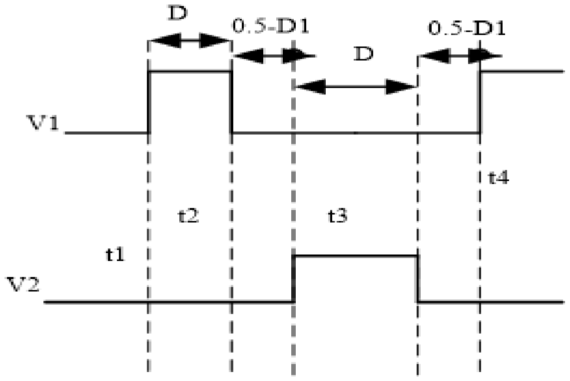

Fig.12. Voltage wave forms of direct and indirect coupled inductors [30]

5.Non-Isolated Coupled Inductor DC-DC Converters

5.1. Floating output inductor coupled dc-dc converter

Generally for high step up applications, isolated current fed dc-dc converters are used which requires an additional fed back and driving circuits. This results in increased converter cost and complexity. In this converter two different types of coupled inductors are used, which are connected in interleaved manner. Here, capacitors $C_{c1,}$ C_{c2} and diodes d_{c1}, d_{c2} are two interleaved clamping circuit's .S_1 and S_2 are the switches operating at high frequency and D_1 and D_2 are used for rectification. First pair, coupled inductors is L_1 and L_2, second, pair coupled inductors are L_3, $L_{4.}$ And C1 and C_2 which are output floating capacitors [41], [42], [43].

To increase the energy gain, reduce electrical energy stress on switches, coupled inductors are used in boost converter. Due to coupled inductor, voltage spike occurs on switches and the spikes can be removed by using capacitor clamps. However, the main drawback in this converter is additional inductor and capacitor is required, due to that circuit complexity increases as shown in Fig.13, [44]-[45]. The floating output integrated inductor dc-dc converter consist of following assumptions,

- All circuit elements are ideal.
- Inductor magnetizing components are equal (Lm1=Lm2)
- Two pairs of coupled inductor turns ratio same.
- Voltage across capacitors Cc1, Cc2, C1 and C2 is same.
- Two pair capacitor values are same (Cc1 =Cc2), (C1=C2).

5.2. Inductor coupled bidirectional dc-dc converter

Bidirectional inductor coupled dc-dc converter circuit is the modified zero voltage transition circuit. The further features added in bidirectional converter use to handle huge power and soft switching technique. The efficiency of bidirectional dc-dc converter is high compared to conventional dc-dc (Buck-Boost) converter. Bidirectional converter operates in buck as well as boost mode [46], [47]. In buck mode of operation dotted line box gives the additional sub-circuit of bidirectional converter and it is used to overcome the energy stress on switches MS3, MS4 and it is used to bring soft switching technique in bidirectional dc-dc converter. Soft switching technique is applied on switches MS1, MS2. With the help of resonance inductor L_r and capacitor C_{ra} is used to achieve zero voltage switching of MS1 and MS2. Alike C_{rb} and L_r is applied zero current switching of MS3, MS4. Here, soft switching technique is applied for inductor coupled bidirectional converter [48], [49].

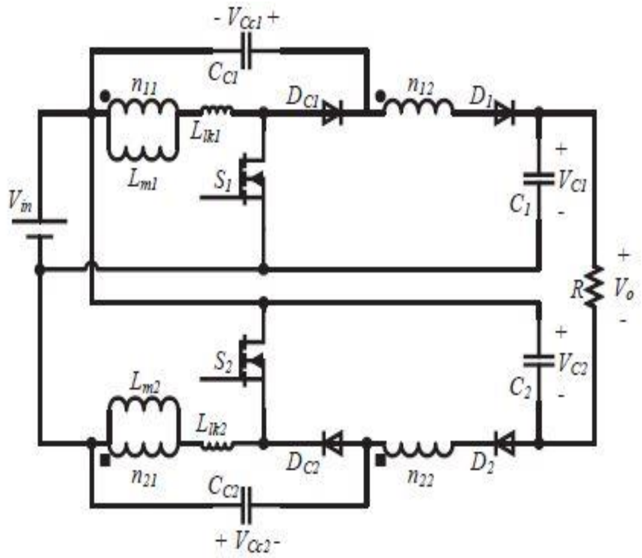

Fig.13. High step up floating output integrated inductor dc chopper [38]

Due to this technique, the converter gives high voltage gain, efficiency and power density. This converter requires additional switches and resonant circuit. As a result, losses are more in this circuit [48], [50]. Bidirectional inductor coupled dc-dc converter is shown in Fig 14.

In boost mode auxiliary switches AS4 and AS5 continuously in off position and no sub-circuit operation is involved on main circuit. Inductor (L_r) current in converter is increasing continuously without interruption. The slope of the inductor current is calculated as,

$$\frac{di_L}{dt} = \frac{V_L - V_{cr}}{L} \tag{27}$$

At initial stage, boost mode operation, resonant capacitor (C_{cr}) voltage is same as inductor voltage.

$$V_{cr} = V_L \tag{28}$$

The converter resonant inductor current, capacitor and frequency is calculated as,

$$i_{Lr} = i_L + \frac{V_L}{6.28 * f * L_r} \tag{29}$$

$$i_{cr} = \frac{V_{Cra}}{6.28 * f * C_{ra}} \tag{30}$$

$$F_r = \frac{1}{6.28 * \sqrt{L_r * C_{ra}}} \tag{31}$$

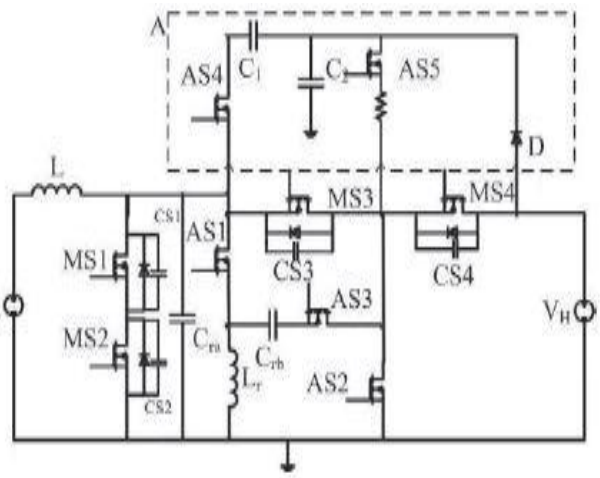

Fig.14. Bidirectional inductor coupled dc-dc converter [46]

5.3. Coupled inductor and built-in transformer dc-dc converter

Coupled inductor and built in transformer dc-dc converter give high energy gain, efficiency and less input current ripple. It requires passive regenerative snubber circuit. In this converter, additional diodes are required [53]. This results in high circuit conduction losses. High turns ratio coupled inductors are used for low input dc supply converters [51], [52]. But it involves with the following disadvantages,

- The input current diversion takes place in tapped winding as a result input current ripples will increase.
- Coupled inductor consists of dc current and creates dc flux. To increase dc current saturation level at exorbitant of increased core volume.

The input current ripple reduces by use of built in transformer energy multiplier cell [54]. Conversion ratio is improved by using a turn's ratio of built in transformer and coupled inductor [53]. Coupled inductor turns are decreased to reduce input current ripple and built in transformer turns ratio n_2 gives an additional design facility of converter for improving system efficiency. Here, V_{in} is supply voltage and C_{in} is input voltage standardizing capacitor. N_{P1} and N_{P2} are coupled inductor turns and N_{S1}, N_{S2} are built in transformer turns. L_{m1}, L_{m2}, L_{k1} and L_{k2} are the magnetizing and leakage inductor components of coupled inductor and built in transformer. Coupling coefficients and turns ratios are calculated as,

$$n_1 = \frac{N_{S1}}{N_{P1}} \quad ; \quad n_2 = \frac{N_{S2}}{N_{P2}} \tag{32}$$

$$x_1 = \frac{L_{m1}}{L_{m1} + L_{k1}} \quad ; \quad x_2 = \frac{L_{m2}}{L_{m2} + L_{k2}} \tag{33}$$

The circuit diagram of Coupled inductor built in transformer dc-dc converter is shown in Fig.15 [55]. Primary side inductor currents i_{L1} , i_{L2} and secondary currents i_{S1}, i_{S2} and magnetizing currents i_{Lm1} and i_{Lm2} .The coupled inductor secondary's and built in transformer are connected in series and secondary side currents i_{s1} and i_{s2} are equal and it is represented as i_s. Primary side currents are calculated as,

$$i_{L1} = i_1 + i_{Lm1} = n_1 i_s + i_{Lm1} \tag{34}$$

$$i_{L2} = i_2 + i_{Lm2} = n_2 i_s + i_{Lm2} \tag{35}$$

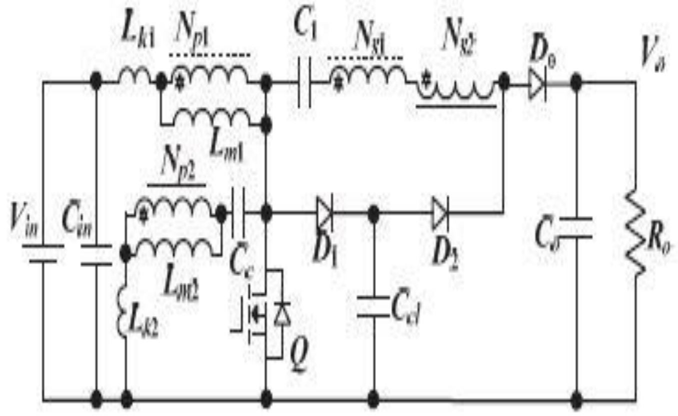

Fig.15. Coupled inductor built in transformer dc-dc converter [55]

5.3.1. Assumptions

The following assumptions are made for Coupled inductor built in transformer dc-dc converter is follows as,

- Supply voltage (V_{in}) is constant.
- Output capacitor value is more than enough to stabilize the output voltage and voltage across each capacitor is constant.

- Converter conduction and diode losses are negotiable [56].

5.4. Inductor coupled Super lift LUO converter

The Super Lift (SL) Luo converter is same as the interleaved enhance converter with switching capacitor [57]. The SL Luo circuit is shown in Fig 16. The voltage increases when voltage cell is inserted between source and load. The benefit of SL Luo converter is follows as,

- The input power is diverted into two smaller sources. As a result, small size and less power rating elements are required.
- Ripple reduction effect decreases the size and power losses of the filters.
- The SL Luo converter gives high voltage gain independent of duty cycle. As a result, low duty cycle operation is enough to step up the input voltage.
- The converter operates at low duty cycle. As a result, the parasitic effects, conduction losses are reduced and efficiency improved [58], [59].

Two Super Lift Luo converters are connected in interleaved mode. As a result, every switch operates at 180^0 out of phase. Based on duty ratio, the converter operates in three modes of operation. If the duty is less than 50%, there is an overlap of off period of switches, If it is equal to 50%, overlap occur either in on or off period of switches [60]. The duty is greater than 50%, there is an overlap of on time of the switches. The converter gain, effective value of inductance and capacitance is calculated as,

$$g = \frac{V_0}{V_{in}} \; ; \quad L_{eff} = \frac{d*(1-d)^2*R}{2*(2-d)*f*\xi} \qquad (36)$$

$$C_{eff} = \frac{V_{in}*(2-d)}{(1-d)+R*\Delta V_{ceff}} \qquad (37)$$

Where, d=duty ratio; f=switch frequency; R=Load resistance; ξ = % ripple in i_L.

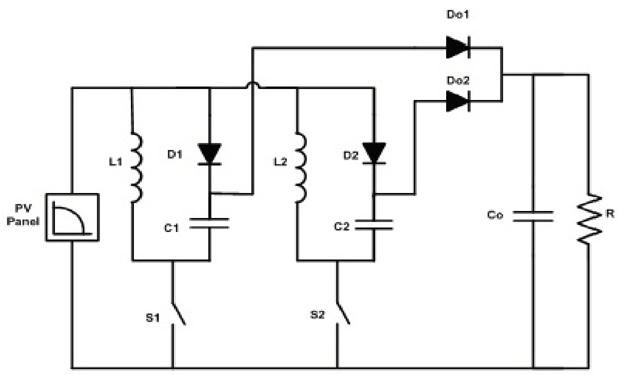

Fig.16. Inductor coupled Super lift LUO converter, [57]

5.5. WIWO dc-dc converter

The combination of buck and boost converters with coupled inductor form wide input, wide output dc-dc converter. The magnetically coupled inductor gives wide step up and wide step down conversion ratio of dc-dc converter. PWM technique is applied for smooth action of switches. WIWO converter operates two modes of operations. In buck mode, the switch S_2 operates at high frequency signals with duty cycle D. Here, S_1 operation in dc-dc operation is complementary to S_2 [61], [62].

Boost mode of operation S_2 operates continuously independent of D. In this converter coupled inductor causes high voltage spikes on switches. As a result, there is a disturbance in switches and converter operation. This converter is used for medium voltage and input power factor correction [63]. The main drawback of this converter is more complex and it requires more number of components compared to conventional boost converter. The circuit of WIWO converter is shown in Fig 17. [64], [65].

The voltage gain of the WIWO converter is calculated as,

$$\frac{V_0}{V_g} = \frac{N+D}{N*(1-D)} \qquad (38)$$

From the circuit voltage gain is equal to the reverse current gain and it is shown in the following equation,

$$\frac{V_0}{V_g} = \frac{I_g}{I_0} \qquad (39)$$

Where,

Vg, Ig = input voltage and current; N=turns ratio; D=duty cycle. Inductors L_1 and L_2 are connected in series, the equivalent inductance and coupling co-efficient is calculated as,

$$L_{eqa} = L_1 + L_2 + 2M \qquad (40)$$

$$M = k\sqrt{L_1 * L_2} \qquad (41)$$

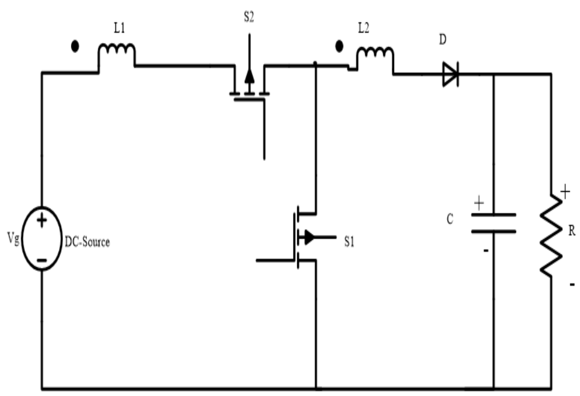

Fig.17. Broad input and broad output dc chopper, [61]

5.6. Double interleaved dc-dc converter

A dc-dc chopper or converter is used to step up the voltage. A basic interleaved enhance converter provide better steady state and dynamic performance compared to other converters, easy ripple cancellation, less ripple value at high frequency and less electromagnetic interference[66], [67], [91]. But it involves increasing usage of components, high cost and more complexity [74] - [76]. The circuit diagram is shown in Fig.18.

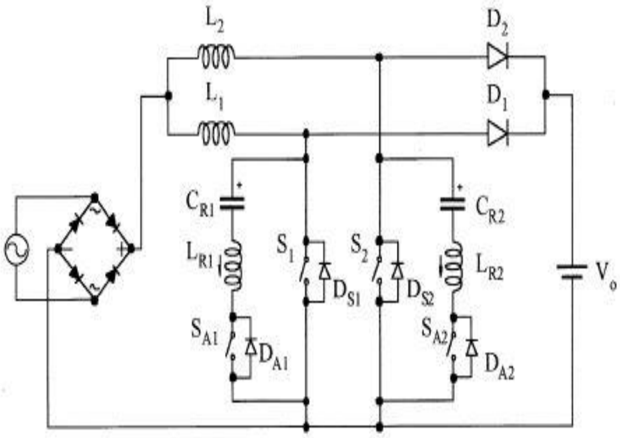

Fig.18. Double interleaved dc-dc converter, [68]

5.7. High efficiency interleaved dc-dc converter

In boost converter, coupled inductor turns are increasing for boosting the input voltage, while maintaining energy stress and leakage energy reasonable. The main drawback is input current distortion. The input current distortion eliminated by using interleaved boost converter. It gives high voltage without varying duty ratio. The passive clamp reduces the reverse recovery losses and voltage stress on switches. This converter is used for low power applications [51], [69], [70], [100].

To overcome the above drawbacks, an interleaved boost converter shares input current into two parts and it is used for industrial high power application [85]. The current stresses on switches are less and the efficiency of the converter is improved [71]. The main drawback is discontinuity of input current. To overcome this drawback, mini-separable switching technique is used, but the circuit complexity increases [72], [73]. The circuit diagram of interleaved converter shown in Fig.19.

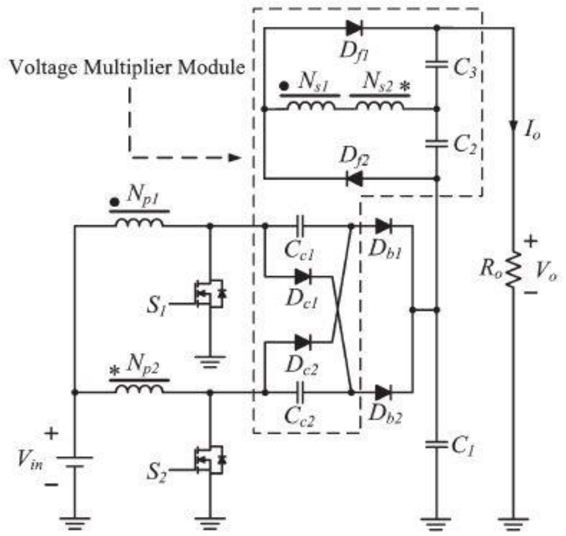

Fig.19. High efficiency interleaved dc-dc converter [77]

5.8. Basic Inductor coupled dc-dc converter

The coupled inductors turns are different and high voltage appears across the diode D_o due to leakage inductance of coupled inductors. So, high power rating semiconductor devices are required. As a result the cost converter is increased [74], [75]. The capacitor C_c is used to decrease the energy pressure across the major switch, second inductor act as voltage source in series with the diode. The reverse leakage problem of converter is eliminated by using capacitor C_0. The main drawback is it requires additional diode and capacitor [76], [77]. The basic Inductor coupled dc-dc converter circuit is shown in Fig.20.

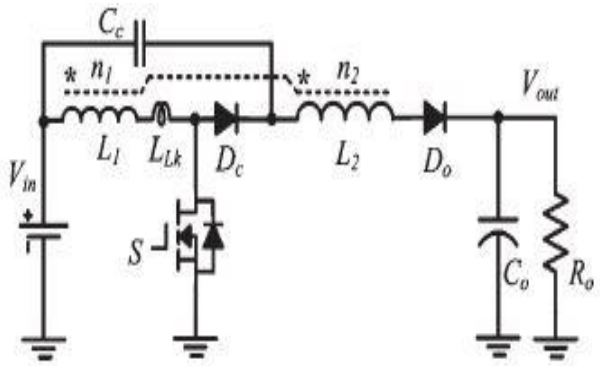

Fig.20. Basic Inductor coupled dc-dc converter [76]

5.9. Fuzzy base capacitor clamp inductor coupled dc-dc converter

As mentioned above, all the dc-dc converters have their own drawbacks. To overcome the above mentioned drawbacks, front end fuzzy logic control based capacitor clamp inductor coupled dc-dc converter is used to improve voltage gain compared to other non-isolated converters for PV grid connected applications [78]. [79], [93]. Here, resister (R_1 –R_2) gives inductor copper losses. Switch S_1 is the MOSFET used for high power applications and a body diode is used to remove reverse recovery voltage across switches. The circuit diagram of fuzzy based inductor coupled converter is shown in Fig 21. This converter gives better steady state and dynamic behavior compared to all other converters. The electrical energy stress on switches is less, less ripple and inductor voltage spikes [80]. The main features of this converter is better voltage gain, less electromagnetic interference, more flexibility and efficiency [81]. The circuit complexity is more compared to other converter but it gives accurate results.

The following assumptions are made while designing fuzzy based capacitor clamp converter.

- All inductor and capacitor losses are negligible.
- Output capacitors (C_1, C_2) values are same.
- Output voltage of the converter is constant.
- Ideal magnetic coupling co-efficient

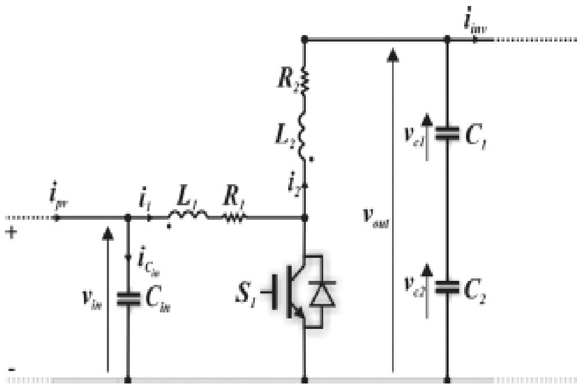

Fig.21. Fuzzy base capacitor clamp inductor coupled dc-dc converter [58]

6. Conclusion

This paper reviews different types of isolated, non-isolated inductor coupled dc-dc converters for photovoltaic grid connected applications and it is compared with the different types of renewable power generation is installed nationally as well as internationally. Every non-isolated inductor coupled dc-dc converter, the advantages, disadvantages, assumptions, applications are discussed and different types of switches using for DC-DC converter performance is analyzed. Among all dc-dc converters, fuzzy technique based capacitor clamp inductor coupled dc-dc converter is preferred by most of researchers to improve the overall system performance and reduce the cost of the converter.

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