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Power Quality Improvement Using Modified SEPIC Converter in Photovoltaic System

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ABSTRACT: The photovoltaic (PV) generation is increasingly popular nowadays, while typical loads require more high-power quality. Basically, one PV generator supplying to nonlinear loads is desired to be integrated with a function as an active power filter (APF). In this project, a three-phase three-wire system, including a detailed PV generator, modified single ended primary inductor converter (M-SEPIC) converter for high voltage conversion and to extract maximum radiation power using maximum power point tracking, and dc/ac voltage source converter to act as an APF, is presented. The instantaneous power theory is applied to design the PV-APF controller, which shows reliable performances. Space vector modulation (SVM) control technique is used in the PV-APF controller for better performance.

KEYWORDS: Photovoltaic, Sepic converter, power quality, Inverter

I. INTRODUCTION

Power supply and power quality have been critical issues in power system recently. The grid-connected photovoltaic (PV) generator has nowadays become more popular because of its reliable performance and its ability to generate power from clean energy resources. The dc output voltage of PV arrays is connected to a modified single ended primary inductor converter (M-SEPIC) converter using a maximum power point tracking (MPPT) controller to maximize their produced energy. Then, that converter is linked to a dc/ac voltage source converter (VSC) to let the PV system push electric power to the ac utility.

The local load of the PV system can specifically be a non- linear load, such as computers, compact fluorescent lamps, and many other home appliances, that requires distorted currents. Development of a means to compensate the distribution system harmonics is equally urgent. In this case, PV generators should provide the utility with distorted compensation capability, which makes currents injected/absorbed by the utility to be sinusoidal. Therefore, the harmonic compensation function can be realized through flexible control of dc/ac VSC. Instantaneous power theory has successfully completed active power filter (APF) designing with good Performance.

However, the PV-APF combination has just been gradually developed for several years. This combination is capable of simultaneously compensating power factor, current imbalance, and current harmonics, and also of injecting the energy generated by PV with low total harmonic distortion (THD).

Even when there is no energy available from PV, the combination can still operate to enhance the power quality of the utility. By another manner in this paper, the proposed PV-APF Controller utilizing power references shows some significant improvements in theory and a simple control topology. The PV-APF system helps the utility supply a unity power factor and pure sinusoidal currents to the local nonlinear loads by generating the oscillating and imaginary components. When there is an excess power, that PV unit will only inject average power to the utility. As a result, this system can be considered as a distributed APF, which is a better solution than adopting passive filters.

The development of high static gain dc–dc converters is an important research area due to the crescent demand of this technology for several applications supplied by low dc output voltage power sources. Some examples are renewable energy sources as low power wind turbine, photovoltaic (PV) modules and other applications as fuel cells, embedded systems, portable electronic equipment, uninterruptable power supply, and battery powered equipment.

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Some requirements are normally necessary in these applications such as reduced losses, high power density, low weight, and volume. The high efficiency operation is particularly important, mainly for battery powered systems and high-cost power sources. An application where the proposed converters can be applied is the photovoltaic energy generation in grid-connected systems using the ac module or micro inverter structure. Generation is the centralized inverter, where several PV modules are connected in series in order to obtain the dc voltage level necessary for the inverter operation and the energy transference to the grid with low-current harmonic distortion. However, a common problem in this structure is the power losses due to the centralized maximum power point tracking (MPPT), mismatch losses among the PV modules, and generation reduction due to a partial shading of the series-connected PV modules. Some of these problems are minimized with the multistring structure, where reduced strings are connected with dc–dc converters with the MPPT algorithm and the output of these dc–dc converters are connected to the inverter input.

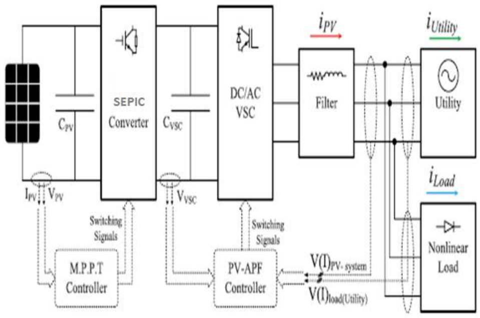

Fig 1. Proposed design of PV-APF combination

II. PV-APF COMBINATION SYSTEM

The detailed PV-APF configuration is shown in Fig. 1, which consists of the following.

1) The PV series-parallel array, which is Sun Power SPR-305-type, delivers a maximum of 10-[kW] power at 1000-W/m2 solar irradiance, assuming that there is no battery storage system connected to the dc bus.
2) ASEPIC converter (dc/dc) implements MPPT by an incremental conductance integral regulator technique, which automatically varies the duty cycle in order to generate the required voltage to extract maximum power.
3) The dc bus is connected to a two-level three-phase dc/ac VSC with a *C*VSC capacitor. The dc/ac VSC converts the ac supplying to local nonlinear loads and connects to a stiff utility.
4) A capacitor bank filters out switching harmonics produced by the dc/ac VSC.
5) The loads include a three-phase diode rectifier supplying a current at dc side and one phase diode rectifier connecting between phase A and phase B to make an overall unbalanced load.
6) This PV-APF combination system is connected directly to the utility for shunt active filter implementation

A.DYNAMIC MODEL OF PV ARRAY

The PV array involves *N* strings of modules connected in parallel, and each string consists of *M* modules connected in series to obtain a suitable power rating. The dynamic model of PV cell is shown in Fig 2.

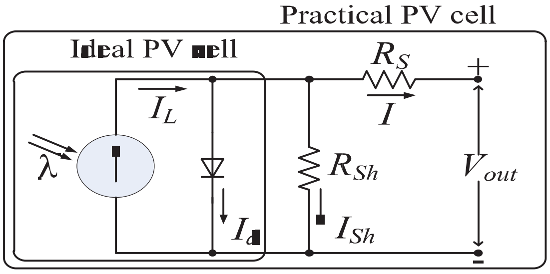

Fig 2. Equivalent electrical circuit of the PV cell.

The output-terminal current I is equal to the light- generated current I_L, less the diode-current $I_d$and the shunt leakage current (or ground-shunt current) I_{Sh}. The series resistance $R_S$represents the internal resistance to the current flow. The shunt resistance R_{Sh} is inversely related to leakage current to the ground. In an ideal PV cell, R_S=0 (no series loss) and R_{Sh}=infinite (no leakage to ground). In a typical high-quality 1-in2 silicon cell, R_S=0:05-0.10 [Ω] and R_Sh=200-300 ohms. The PV conversion efficiency is sensitive to small variations in R_S, but is insensitive to variations in R_{Sh}. A small increase in $R_S$can decrease the PV output significantly. The two most important parameters widely used for describing the cell electrical performance are the open-circuit voltage Voc =Vout+$R_S I$ obtained when the load current is zero (I=0) and the short-circuit current Isc. Ignoring the small diode and the ground-leakage currents under zero terminal voltage, the short-circuit current under this condition is the photocurrent I_L. The PV modules are modeled approximately as a constant current source regarding the electrical analysis.

B.MODIFIED SEPIC CONVERTER

The development of high static gain dc–dc converters is an important research area due to the crescent demand of this technology for several applications supplied by low dc output voltage power sources. Some examples are renewable energy sources as low power wind turbine, photovoltaic (PV) modules and other applications as fuel cells, embedded systems, portable electronic equipment’s, uninterruAptable power supply, and battery powered equipment. Some requirements are normally necessary in these applications such as reduced losses, high power density, low weight, and volume. The high efficiency operation is particularly important, mainly for battery powered systems and high-cost power sources. An application where the proposed converters can be applied is the photovoltaic energy generation in grid-connected systems using the ac module or micro inverter structure.

The usual structure used for high-power grid-connected photovoltaic generation is the centralized inverter, where several PV modules are connected in series in order to obtain the dc voltage level necessary for the inverter operation and the energy transference to the grid with low-current harmonic distortion. However, a common problem in this structure is the power losses due to the centralized maximum power point tracking (MPPT), mismatch losses among the PV modules, and generation reduction due to a partial shading of the series-connected PV modules. Some of these problems are minimized with the multistring structure, where reduced strings are connected with dc–dc converters with the MPPT algorithm and the output of these dc–dc converters are connected to the inverter input.

However, in residential applications, most research is focused on the module-integrated converters where the energy generated by a single PV module is transferred to the grid by a dedicated converter integrated with the PV module. Some of the main advantages of this PV generation structure are the modularity, allowing an easy increase of the installed power, the individual MPPT and reduction of the partial shading and panel mismatching effects, thus improving the energy-harvesting capability. However, there are some design challenges in an AC module structure as the efficiency improvement, cost reduction, and the reliable operation throughout the module lifetime. An alternative for the ac module implementation is a two-stage topology as presented.

The operation with high efficiency is a problem for the dc–dc converter due to the low input voltage, high input current, high output voltage, and static gain. Commercial mono crystalline and multi crystalline PV module presents normally a maximum output power (*P*MPP) lower than 350Wwith maximum power point voltage (VMPP) range from 15 to 40V. Common specifications depending on the number of photovoltaic cells are *P*MPP = 100 W with *V*MPP = 15 V, *P*MPP = 200 W with *V*MPP = 30 V and *P*MPP = 300 W with *V*MPP = 40 V. In this study, the specification of *P*MPP = 100 W with *V*MPP = 15 V was considered, but increasing the PV module power, the voltage also increases at the maximum power point. Under this condition, dc–dc converter input current and the converter conduction losses are maintained almost at the same level. When a high step-up ratio is necessary for the implementation of the first power stage, the usual solution is the use of isolated dc–dc converters.

The transformer turns ratio allows us to increase the converter static gain. However, the isolated solution presents some problems as the efficiency reduction due to the power transformer losses and intrinsic parameters as the leakage inductance. The power transformer also presents an important contribution in the converter weight and volume. The power converters used with renewable energy sources must present a high efficiency due to the high cost of the energy source, as photovoltaic module or fuel cells. Also in embedded systems and portable equipment’s, the converter power density is an important design parameter. Therefore, the solutions that allow the elimination of the power transformer can improve the efficiency and power density of the power conversion system.

However, the classical non isolated dc–dc converters present a limited step-up static gain ($q = Vo/Vi$).

The boost converter is the classical non isolated step-up dc–dc converter and normally can operate with an adequate static and dynamic performance with a duty cycle close to D = 0.8 resulting in an output voltage around five times the input voltage. A static gain equal to q = 5 is a limited value for the applications considered in this study.

Therefore, three static gain ranges are considered in this paper. A dc–dc converter operating with a static gain range until $q = 5$ is considered a standard static gain, a static gain range higher than $q = 10$ is considered a high static gain solution and an operation with static gain higher than $q = 20$ is considered a very high static gain solution. The main desired characteristics in the considered applications are a static gain equal or higher than ten times, low switch voltage, low input current ripple, reduced weight and volume, and high efficiency.

Many techniques were developed in order to increase the static gain of the non-isolated structures for the implementation of high efficiency and high power density solutions. A review of the main techniques proposed is presented in. The most part of the proposed solutions of non-isolated high static gain dc–dc converter are based on the boost topology with an additional technique associated. The main techniques used are the switch capacitors and voltage multiplier cells, switched inductors, inductor magnetic coupling and also combinations of these techniques as the integration of the voltage multiplier cell with the inductor magnetic coupling. The base topology presented in this paper is a modification of the SEPIC dc–dc converter and the main operation characteristics obtained with this modification comply with the requirements necessary in the high static gain applications.

The basic structure without magnetic coupling presents a static gain close to twice of the classical boost converter and the switch voltage is close to half of the value obtained with the classical boost converter in the operation with high values of the duty cycle. The proposed solution using a magnetic coupling is obtained including a secondary winding in an inductor of the converter, operating as a fly back transformer, increasing the static gain.

However, due to the configuration of the power circuit proposed, the usual problems presented by the single switch isolated dc– dc converter are not presented by the proposed structure with transformer. Only part of the power processed by the converter is transferred to the output through the coupling inductor and another part of the power is transferred directly by the non-isolated converter, reducing the weight, volume, and losses of the transformer. The leakage inductance is a problem for the single-switch isolated dc–dc converters resulting in the switch overvoltage, and the energy stored in the leakage inductance must be dissipated in snubber or clamping circuits. However, the leakage inductance is necessary in the proposed converter with transformer in order to obtain ZCS turn-on commutation and to reduce the diodes reverse recovery current, increasing the converter efficiency.

The energy stored in the leakage inductance is transferred to the converter output through the diodes and capacitor of the circuit. The voltages in all semiconductors are clamped by the intrinsic converter operation without dissipative components. The theoretical and experimental analysis of the modified SEPIC dc–dc converter is developed in this paper for low dc input voltage and high output voltage applications. The topology using the magnetic coupling with the inclusion of an inductor auxiliary winding operating as a fly back transformer is also presented and studied in this paper in order to increase the static gain maintaining low switch voltage.

OPERATIONS

i)Mode 1 [t0−t1]

The power switch S is conducting and the input inductor L1 stores energy. The capacitor CS2 is charged by the secondary winding L2S and diode DM2. The leakage inductance limits the current and the energy transference occurs in a resonant way. The output diode is blocked, and the maximum diode voltage is equal to (Vo−VCM) instant t1, the energy transference to the capacitor CS2 is finished and the diode DM2 is blocked

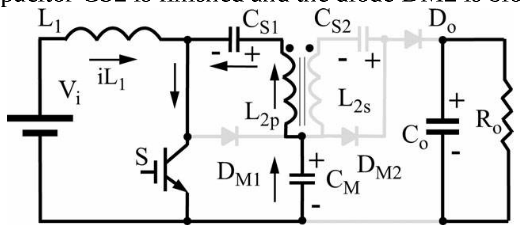

Fig 3. Mode 1 [t0−t1]

ii)Mode 2 [t1−t2]

From the instant t1, when the diode DM2 is blocked, to the instant t2 when the power switch is turned OFF, the inductors L1 and L2 store energy and the currents linearly increase.

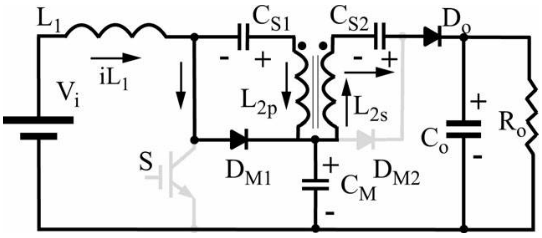

Fig 4. Mode 2 [t1−t2]

iii)Mode 3 [t2−t3]

At the instant t2 the power switch S is turned OFF. The energy stored in the L1 inductor is transferred to the CM capacitor. Also, there is the energy transference to the output through the capacitors CS1, CS2 inductor L2 and output diode Do.

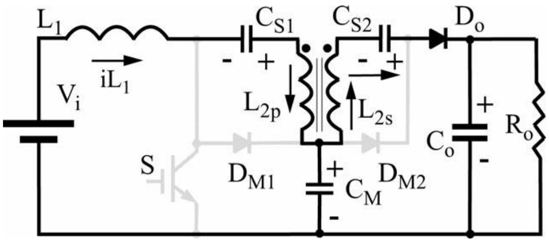

Fig 5. Mode 3 [t2−t3]

iv) Mode 4 [t3−t4]

At the instant t3, the energy transference to the capacitor CM is finished and the diode DM1 is blocked. The energy transference to the output is maintained until the instant t4, when the power switch is turned ON.

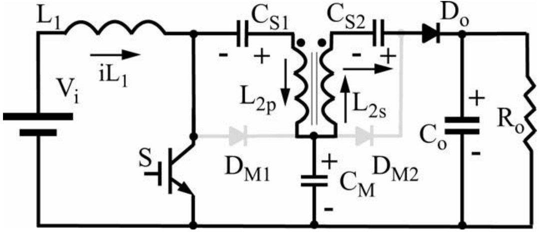

Fig 6. Mode 4 [t3−t4]

v)Mode 5 [t4−t5]

When the power switch is turned ON at the instant t4 , the current at the output diode Do linearly decreases and the di/dt is limited by the transformer leakage inductance, reducing the diode reverse recovery current problems. When the output diode is blocked, the converter returns to the first operation stage.

C.MPPT IN M-SEPIC CONVERTER

The cell produces the maximum power at voltage corresponding to the knee point of the *I-V* curve, as shown in Fig. 3. *V*max and *I*max are voltage and current at maximum power point, respectively. The dc/dc converter is set to operate at optimal voltage to achieve maximum power by MPPT algorithm. In this paper, switching duty cycle is optimized by the MPPT controller that uses the incremental conductance and integral regulator technique. This MPPT method is based on the fact that the power slope of the PV is null at MPP point (where $dp/dv=0$), positive in the left, and negative in the right. The regulator output of MPPT is the duty cycle correction for semiconductor switches.

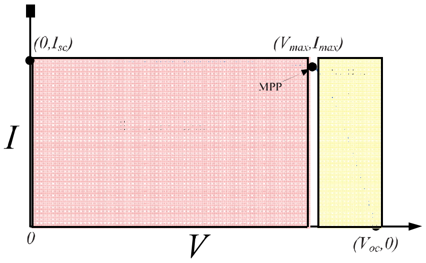

Fig 7. I-V curve and remarkable points.

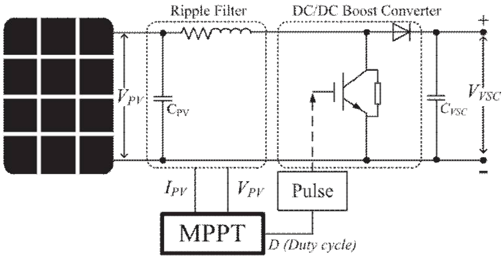

Fig 8. Controller mechanism of the SEPIC converter.

III. INSTANTANEOUS POWER BALANCE

Instantaneous power flow among the parts of the PV-APF system simplified in Fig. 5 is a compromise between technical constraints and designed targets. The dc/dc boost converter regulates its semiconductor switches to extract the maximum power generated by PV array (p_{PV}).

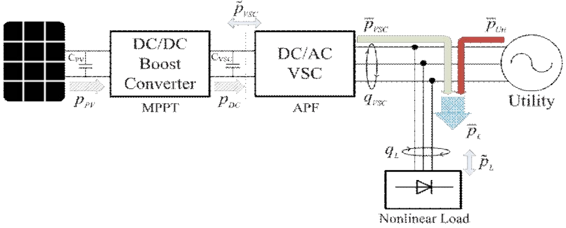

Fig 9. Instantaneous power flows among the PV-APF system.

The MPPT methods could be chosen appropriately in any specific circumstance. Beyond that converter with the power output p_{DC}, the dc/ac VSC keeps a significant role in implementing a given control duty. At the dc side, the power concept is consistent. However, at the ac side, the instantaneous power includes both the active part (p_{VSC}) and the imaginary part (q_{VSC}). The losses at the dc/dc boost converter and the dc/ac VSC are ignored.

The load demand includes real power and imaginary power. In general, the real and imaginary power include two parts: 1) an average (superscript N) one, and 2) an oscillating (superscript Q) one, which are realized through a low-pass filter.

In this paper, the dc/ac VSC supplies harmonic and imaginary parts for the nonlinear loads (q_L) in addition to the normal duty, which is to convey the active power (p_{VSC}) from the PV unit. Different from pure linear loads that consume only average active power component, the nonlinear loads also consume the oscillating components. The APF function results in pure sinusoidal currents from the utility. Consequently, the PV-APF combination has to supply the oscillating components and one part of the average component of both real and imaginary power demand utilizing the PV output power.

IV. CONTROLLERS FOR DC/AC CONVERTER

In this section, the controllers for dc/ac VSC based on instantaneous power theory and instantaneous power balance are presented. In a conventional way, the *dq*-current controller is used to inject maximum real power from PV and zero reactive power to keep unity power factor of the utility. While a nonlinear load is connected close to PV position, the proposed unique PV-APF controller should be used to compensate the harmonics and help transfer the PV power. At night (no irradiance and no battery) or when there is no PV array, the APF controller is switched into the system in order to operate the *C*VSC capacitor just for an APF purpose.

A. PV-APF CONTROLLER

The dc/ac VSC integrated by an APF function should provide the harmonic elimination and reactive power compensation and simultaneously inject the maximum power generated by PV units. The controller is established based on the instantaneous power theory, where all the parameters are processed instantaneously.

Furthermore, the dc-link voltage regulation passes through a PI-controller via the LPF, which filters out the switching harmonics existing in the dc capacitor voltage. Eventually, reference powers are passed to a current references calculation block. These ideas make the following equations. The complete algorithm of a controller for three-phase three-wire dc/ac VSC that compensates oscillating real power and oscillating imaginary power, and supplies real power of load. The hysteresis control technique is used to switch insulated-gate bipolar transistor gates.

B. APF CONTROLLER

This section reminds the topology of well-known APF controllers based on instantaneous power theory. The utility currents are not measured by this controller. Only the load currents and the output currents of the APF are measured. The greatest difference of this controller compared with the PV-APF controller is the calculated reference values generated from *C* VSC, which are oscillating powers. In this case, the utility must supply the constant dc-link voltage regulation.

V. SIMULATION

The system is simulated in MATLAB/Sim power Systems to test the PV-APF unit, which connects directly to the ac-utility, and to validate its ability to Filter out the harmonic of nonlinear loads.

A. SIMULATION CIRCUIT

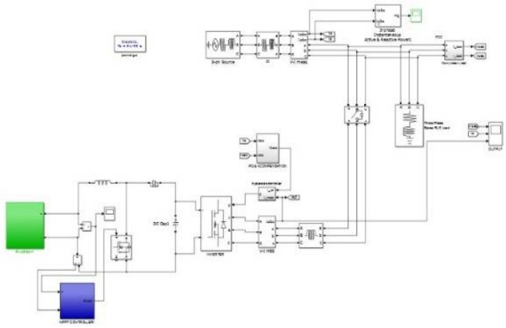

Fig 10 Simulation Circuit

The APF controller mode requires only *C*VSC for the APF purpose when the PV unit generates zero power. In short, there are four modes of running simulation, as clarified.

B. SIMULATION OUTPUT

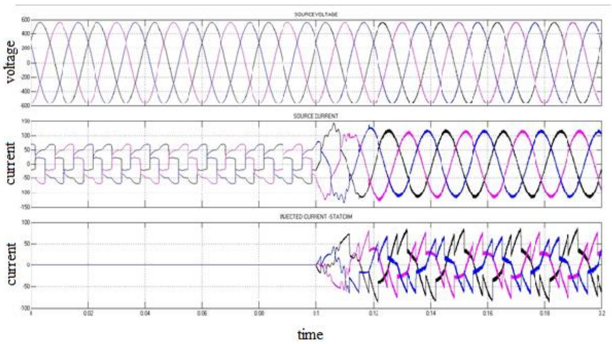

Fig 11. Simulation Output

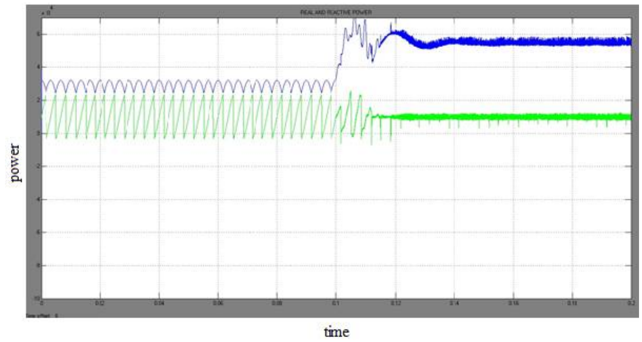

Fig 12. Real power and reactive power

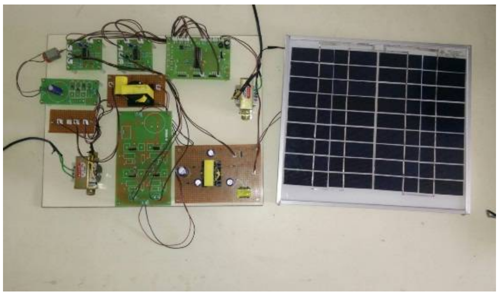

Fig 13. Hardware module

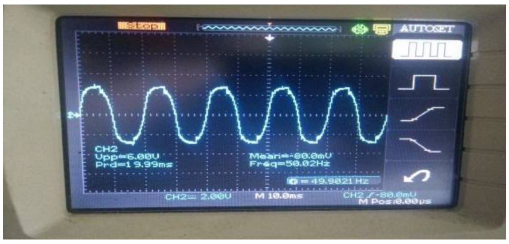

Fig 14. CRO output

X. CONCLUSION

Two new topologies of non-isolated high static gain converters are presented in this project. The first topology without magnetic coupling can operate with a static gain higher than 10 with a reduced switch voltage. The structure with magnetic coupling can operate with static gain higher than 20 maintaining low the switch voltage. The efficiency of proposed converter without magnetic coupling is equal to 91.9% operating with input voltage equal to 15 V, output voltage equal 150 V, and output power equal 100 W. The efficiency of the proposed converter with magnetic coupling is equal to 92.2% operating with input voltage equal to 15V, output voltage equal 300V, and output power equal 100W. The commutation losses of the proposed converter with magnetic coupling are reduced due to the presence of the transformer leakage inductance and the secondary voltage multiplier that operates as a non-dissipative clamping circuit to the output diode voltage. By using modified single ended primary inductor converter (SEPIC) based PV inverters we achieved high power quality in the utility grid, high voltage gain and perform soft-switching operation. Also system efficiency is improved. To make this as a product, we need to use high quality controller which reduce maximum harmonics. The MATLAB/Sim power Systems simulation shows good performances of this controller. The positive influence of MPPT on maximizing PV power output is also validated.

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