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A High Voltage Gain SEPIC Converter for Grid Connected PV Application

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Abstract-*This paper proposes an implementation of Single Ended Primary Inductor Converter (SEPIC) and Voltage Source Inverter for an Induction Motor using Photovoltaic energy as a source. Generally the larger number of drives employed for industrial and commercial applications are induction motor drives. In this paper SEPIC converter (DC-DC converter) with grid connected and induction motor applications, a voltage source inverter with sinusoidal pulse width modulation is implemented on it to attain sufficient voltage to drive three phase induction motor. The simulation work of these SEPIC converter and voltage source inverter fed induction motor circuits have been done using MATLAB/SIMULINK software.*

Index Terms—DC–DC power conversion; voltage multiplier and solar power generation; renewable energy sources

I.INTRODUCTION

The photovoltaic energy system has the advantages of absence of fuel cost, no environmental impacts, low maintenance and lack of noise and also it is a kind of renewable energy system. So it is becoming popular in the recent years, as a resource of energy. Modeling and simulation of PV array based on circuit model and mathematical equations are proposed [4]. As the photovoltaic (PV) cell exhibits the nonlinear behavior, while matching the load to the photovoltaic modules, DC-DC power converters are needed. There are several converter configurations such as Buck, Boost, Buck-Boost, SEPIC, ĆUK, Fly-back, etc. Buck and Boost configurations can decrease and increase the output voltages respectively, while the others can do both functions. Buck, Boost, Buck Boost converters as interface circuits are proposed and analyzed in [2]. CUK and SEPIC converters are analyzed in [1-3].

Renewable Energy Sources are those energy sources which are not destroyed when their energy is harnessed.
Human use of renewable energy requires technologies that harness natural phenomena, such as sunlight, wind, waves, water flow, and biological processes such as anaerobic digestion, biological hydrogen production and geothermal heat. Among these solar and wind energy with wind turbines appears to be the most promising source of renewable energy. The power electronics is changing the basic characteristic of the wind turbine from being an energy source to be an active power source. In recent years, hybrid PV/wind system (HPWS) has become viable alternatives to meet environmental protection requirement and electricity demands. With the complementary characteristics between solar and wind energy resources for certain locations, hybrid PV/wind system presents an unbeatable option for the supply of small electrical loads at remote locations where no utility grid power supply. The other advantage of solar / wind hybrid system is that when solar and wind power production is when used together, the reliability of the system is enhanced. Since they can offer a high reliability of power supply, their applications and investigations gain more concerns nowadays.
Water supply is one of the principal problems in all parts of the world. With increasing population need for water has also increased. In India, electrical and diesel powered water pumping systems are widely utilized for irrigation applications. The continuous exhaustion of conventional energy sources and their environmental impacts have created an interest in choosing RESs such as solar-photovoltaic, solar-thermal, wind energy, producer gas and biomass sources to power water pumping systems [5] which uses water in the most effective manner. A recently proposed solution to this problem is the use of autonomous wind generators to electrically propel centrifugal water pumps. Autonomous water pumping system based on wind generation and control by rotor frequency is possible [6]. The power flow control is performed through the rotor winding of the generator by changing the frequency and

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voltage of its excitation. The need for the optimum utilization of water and energy resources has become a vital issue during the last decade, and it will become more essential in the future.

II. SOLAR ENERGY SYSTEM

Solar energy is the easily available and has immense potential to generate energy. It is non-polluting and is for free. It is only through the photovoltaic effect that sunlight can be converted directly into electricity. This feature of directness of conversion has been largely responsible for making photovoltaic such a popular mode of generation of electricity. Earth surface receives 1.2x1017 W of power from sun. Energy supplied by the sun in one hour is almost equal to the amount energy required by the human population in one year. On an average the sunshine hour in India is about 6hrs annually also the sun shine shines in India for about 9 months in a year. Solar Energy is a good choice for electric power generation. The solar energy is directly converted into electrical energy by solar photovoltaic module. Solar powered water pumping systems consists of PV array, motor and pump. Depending on the system design, it requires storage batteries and charge regulator. The motor is chosen according to power requirement and the type of current output of the system. Battery less system is considered to be more economical. The use of solar photovoltaic energy is considered to be a primary energy source for countries located in tropical regions with solar radiation upto 1000W/m2.

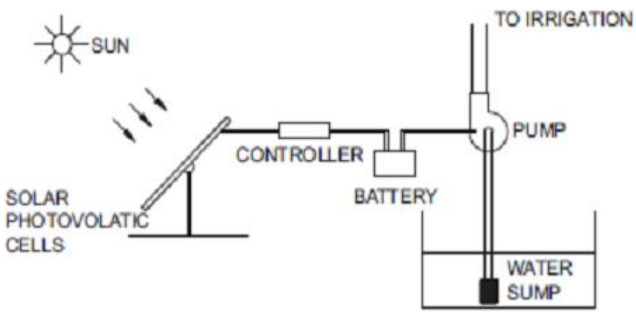

Fig.1.Layout of solar photovoltaic pumping system.

PV Array: The PV array is constructed by many series or parallel connected solar cells [7]. Each solar cell is formed by a junction semiconductor, which can produce currents by the photovoltaic effect. The main technical factors over the past decade that have led to improved PV system performance include

- Improved PV module Cell manufacturing techniques and scale that have lowered PV module costs and resulted in higher module efficiency.
- Improved inverter performance (better efficiency, reliability, lower cost, improved protection and monitoring features).
- More effective application, design and integration of PV systems and standardized interconnection requirements for grid interaction system.
- Subsidies provided by the governments.

III. WIND ENERGY SYSTEM

Wind power is the conversion of wind energy into a useful form of energy, such as using wind turbines to make electrical power, wind mills for mechanical power, wind pumps for water pumping or drainage, or sails to propel ships. Large wind farms consist of hundreds of individual wind turbines which are connected to the electric power transmission network. For new constructions, onshore wind is an inexpensive source of electricity, competitive with or in many places cheaper than fossil fuel plants. Small onshore wind farms provide electricity to isolated locations. As of 31 Jan 2013 the installed capacity of wind power in India was 18634.9MW, India ranking the 5th largest country in terms of installed wind capacity. A wind turbine obtains its power input by converting the force of the wind into torque (turning force) acting on the rotor blades. The amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed. There are basically two types of wind turbine available-

1. Vertical Axis Wind Turbine (VAWT)
2. Horizontal Axis Wind Turbine (HAWT)

The mechanical power generated by wind turbine in order to describe the power characteristic is given by

Pm = 0.5 ρ A Cp(λ, β)Vw3

Where

ρ = air density

A = rotor swept area

C

p(λ, β) = power coefficient function

β = pitch angle

VW = velocity of wind

A wind powered rotor is coupled to a synchronous generator with permanent magnets, which convert the wind energy into electrical power energy. The generator is then coupled to a common induction motor, which drives a centrifugal pump for water pumping.

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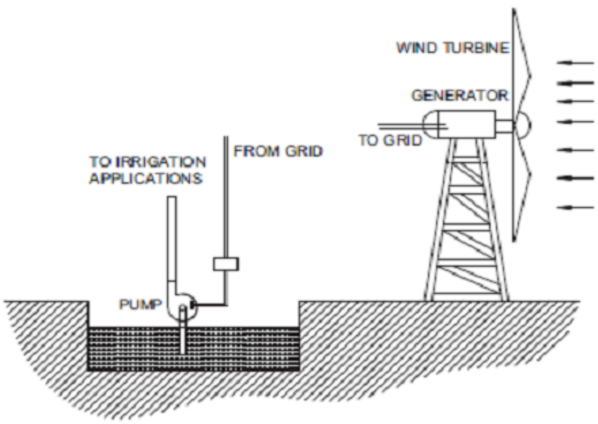

Fig.2.Layout of wind powered pumping system.

IV. HYBRID SOLAR WIND ENERGY SYSTEM

Hybrid systems as the name says, is the integration of two or more sources, here wind and solar. Here a multi input converter is employed. It offers higher reliability and flexibility. Even if one source is unavailable, the other can provide the required or smaller power, thus ensuring continuous power supply. Multiple-input converter (MIC) for hybrid power systems is attracting increasing attention because of reduced components, compactness and centralized control [8-9]. The MICs proposed in [10] are essentially based on parallel connection at the output of a number of boost converters and buck-boost converters. Such MICs do not enjoy the advantage of reduced device counts.

The objective of this paper is to propose a novel multi input inverter for grid-connected hybrid PV/wind power system. The proposed multi-input inverter has the following advantages:

1) Power from the PV array or the wind turbine can be delivered to the utility grid or the load.

2) A large range of input voltage variation caused by different insolation and wind speed is acceptable.

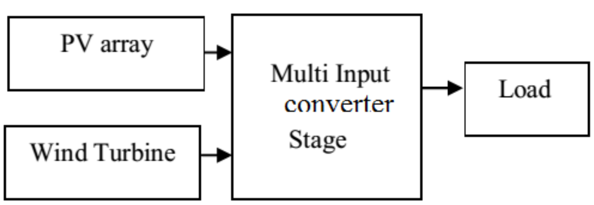

Fig.3.Block diagram of multi input converter.

V.PROPOSED CONVERTER WITHOUT MAGNETIC COUPLING

A. Power Circuit without Magnetic Coupling

The step-up and step-down static gain of the SEPIC converter is an interesting operation characteristic for a wide input voltage range application. However, the switch voltage is equal the sum of the input and output voltages, and the static gain is lower than the classical boost converter. The modification of the SEPIC converter is accomplished adding only two components with the inclusion of the diode DM and the capacitor CM, as presented in Fig.4. Many operational characteristics of the classical SEPIC converter are changed with the proposed modification, as the elevation of the converter static gain. The capacitor CM is charged with the output voltage of the classical boost converter. The polarity of the CS capacitor voltage is inverted in the proposed converter and the expressions

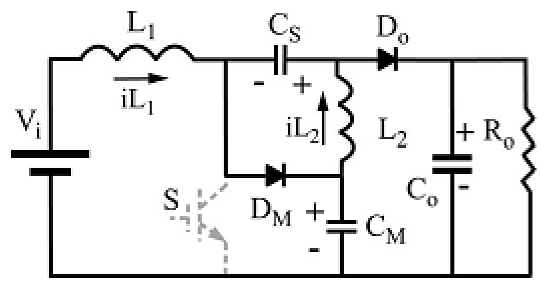

Fig.4. First operation stage.

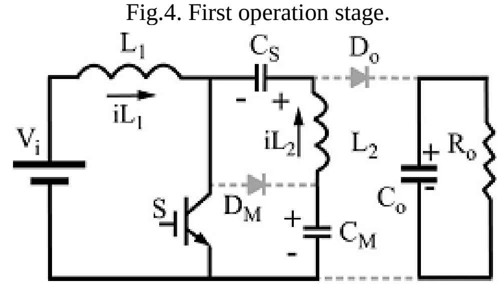

Fig.5.Second operation stage.

of the capacitors voltages and other operation characteristics are presented in the theoretical analysis. The continuous conduction mode (CCM) of the modified SEPIC converter presents two operation stages. All capacitors are considered as a voltage source and the semiconductors are considered ideals for the theoretical analysis.

1) First Stage [t0−t1](Fig.4): At the instantt0, switch S is turned-off and the energy stored in the input inductor L1 is transferred to the output through the CS capacitor and output diode Do and also is transferred to the CM capacitor through the diode DM. Therefore, the switch voltage is equal to the CM capacitor voltage. The energy stored in the inductor L2 is transferred to the output through the diode Do.

2) Second Stage [t1−t2](Fig.5):At the instantt1, switch Sis turned-on and the diodes DM and Do are blocked and the inductors L1 andL2 store energy. The input voltage is applied to the input inductor L1 and the voltage VCS−VCM is applied to the inductor L2.The VCM voltage is higher than the VC voltage. The main theoretical waveforms operating with hard switching commutation are

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presented in Fig.6. The maximum voltage in all diodes and in the power switch is equal to the CM capacitor voltage. The output voltage is equal to the sum of the CS and CM capacitors voltage. The average L1inductor current is equal to the input current, and the average L2 inductor current is equal to the output current. The static gain of the proposed converter can be obtained considering null the average inductors voltage at the steady state and it is presented in (1) considering the CCM operation. The static gain of the proposed converter is higher than the obtained with the classical boost

$$\frac{V_0}{V_i} = \frac{1+D}{1-D} \tag{1}$$

The CM capacitor voltage is calculated by (2) that is the same output voltage of the classical boost converter. The maximum switch voltage is equal to the VCM voltage. Therefore, the switch

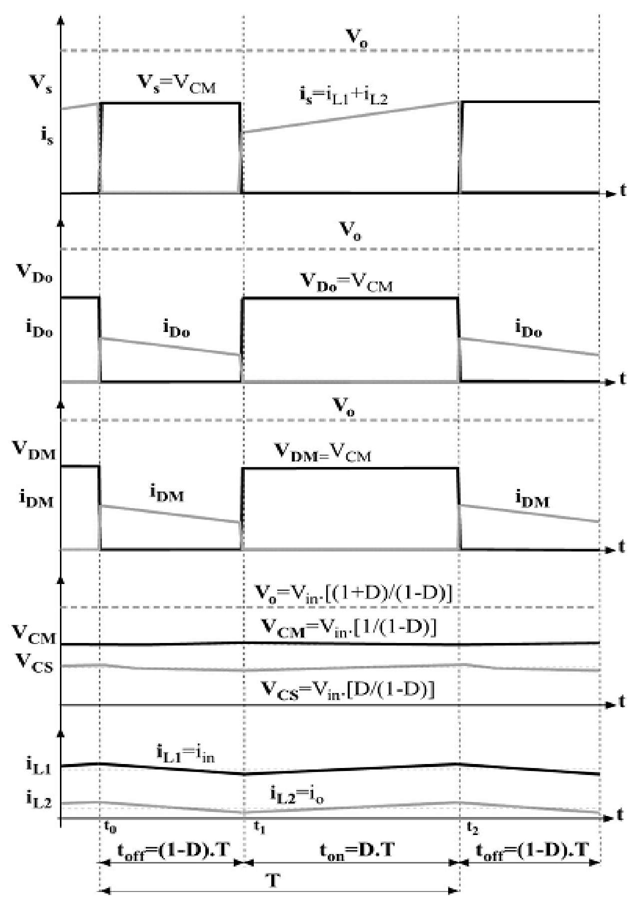

Fig.6. Main theoretical waveform.

Voltage will be lower than the converter output voltage

$$\frac{V_{cm}}{V_m} = \frac{1}{1-D} \tag{2}$$

The voltage across the CS capacitor is calculated by (3)

$$\frac{V_{cs}}{V_i} = \frac{D}{1-D} \tag{3}$$

The static gain of the classical SEPIC, boost and modified SEPIC converters are presented in Fig.7 As it can be observed in this figure, with a duty cycle equal to D=0.818, a static gain equal to 10 is obtained, and the switch voltage is equal to 5.5 times the input voltage. Therefore, the switch voltage is close to half of the output voltage. The theoretical analysis, operation stages, and waveforms of the modified SEPIC converter operating in discontinuous conduction mode (DCM) is not presented in this paper. However, the static gain and the CM and CS capacitor voltages operating in DCM are presented in (4), (5), and (6), respectively

$$\frac{V_o}{V_i} = 1 + \frac{V_i \cdot D^2}{2 \cdot i_o \cdot L_{eq} \cdot f} \tag{4}$$

$$\frac{V_{CM}}{V_i} = 1 + \frac{V_i \cdot D^2}{4 \cdot i_o \cdot L_{eq} \cdot f} \tag{5}$$

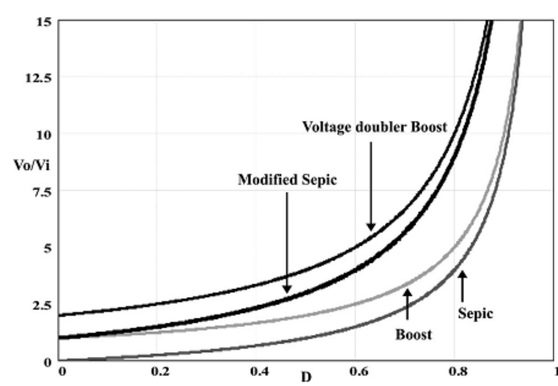

Fig .7 Converters static gain.

$$\frac{V_{cs}}{V_i} = \frac{V_i.D^2}{4.i_0.L_{eq}.f} \tag{6}$$

$$L_{eq} = \frac{L_1 \cdot L_2}{L_1 + L_2} \tag{7}$$

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VI.PROPOSED CONVERTER WITH MAGNETIC COUPLING

A. Power Circuit with Magnetic Coupling

The modified SEPIC converter without magnetic coupling can operate with the double of the static gain of the classical boost converter for a high duty-cycle operation. However, a very high static gain is necessary in some applications. A practical limitation for the modified SEPIC converter in order to maintain the converter performance is a duty cycle close to D=0.85,resulting in a maximum static gain equal toq=12.3.Asimple solution to elevate the static gain without increases the duty cycle and the switch voltage is to include a secondary winding in the L2 inductor. The L2 inductor operation is similar to aback–boost inductor and a secondary winding can increases the output voltage by the inductor windings turns ratio (n), operating as a fly back transformer. Fig.8 shows this alternative circuit. However, this converter structure presents the problem of over voltage at the output diode Do due to the existence of the coupling winding L2 leakage inductance. The energy stored in the leakage inductance, due to the reverse recovery current of the output diode, results in voltage ring and high reverse voltage at the diode Do. This overvoltage is not easily controlled with classical snubber or dissipative clamping. A simple solution for this problem is the inclusion of a voltage multiplier at the secondary side as presented in Fig.9This voltage multiplier increases the converter static gain, the voltage across

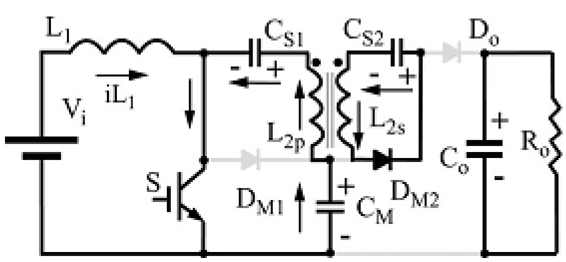

Fig.8. First operation stage.

Diode is reduced to a value lower than the output voltage and the energy stored in the leakage inductance is transferred to the output. Therefore, the secondary voltage multiplier composed by the diodeDM2 and capacitorCS2 is also a non dissipative clamping circuit for the output diode. The circuit presented in Fig.8 is the power circuit studied in this paper. The solutions based on the classical boost converter with magnetic coupling or the integration of the magnetic coupling and the voltage multiplier cell can present very high voltage gain and an excellent performance as presented in [11]–[12]. However, as the magnetic coupling is accomplished with the input inductor in the boost-based solutions, the input current ripple is significantly increased and depends on the inductor winding turns ratio. Increasing the inductor turns ratio and the static gain, the input current ripple rises. The input current ripple increment is a non desirable operation characteristic for some applications as the fuel cell power source. As the magnetic coupling is not accomplished with the input inductor in the proposed topology, the input current ripple is low and is not changed by the magnetic coupling. There are also some proposed solutions based on the integration of the SEPIC converter with boost and fly back dc–dc converters. An isolated active clamp SEPIC-fly back converter is presented in [13] in order to obtain high efficiency. However, the proposed topology presents pulsating input current, and the active clamp technique increases the converter complexity with an additional controlled switch and command circuit. The integration of the boost converter with a SEPIC converter is also proposed in [14] and [15]. Some operation characteristics of this converter are similar to the circuit with magnetic coupling proposed in this paper. The main differences of the proposed converter with respect the previous topology are the ZCS switch turn-on obtained with a resonant operation stage, reducing the commutation losses even in the operation with light load and a higher static gain considering the same transformer turns ratio, reducing the converter duty cycle and the switch voltage. The CCM operation of the modified SEPIC converter with magnetic coupling and output diode clamping presents five operation stages. All capacitors are considered as a voltage source, and the semiconductors are considered ideals for the theoretical analysis.

1) First Stage [t0−t1] (Fig.8): The power switch S is conducting and the input inductorL1 stores energy. The capacitorCS2is 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).At the

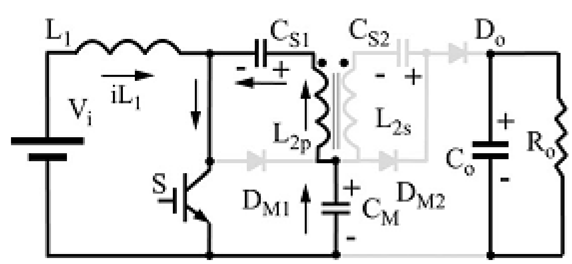

Fig.9. Second operation stage

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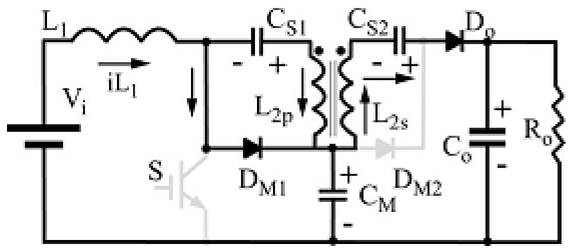

Fig.10. Third operation stage

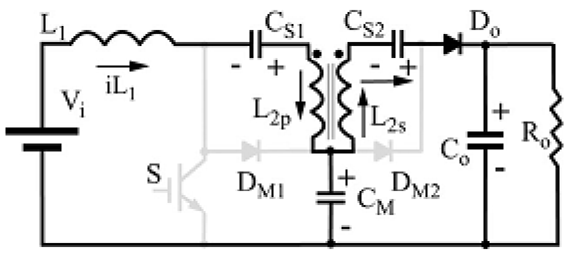

Fig.11. Fourth operation stage.

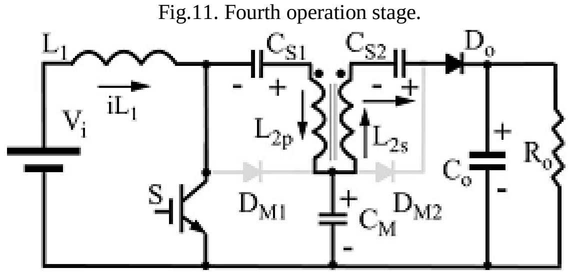

Fig.12. Fifth operation stage.

Instant t1, the energy transference to the capacitor CS2 is finished and the diode DM2 is blocked.

2) Second Stage [t1−t2] (Fig 9): From the instantt1, when the diodeDM2 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.

3) Third Stage [t2−t3] (Fig .10): At the instant t2 the power switch S is turned OFF. The energy stored in theL1inductor is transferred to the CM capacitor. Also, there is the energy transference to the output through the capacitorsCS1, CS2 inductor L2 and output diode Do.

4) Fourth Stage [t3−t4] (Fig11): At the instantt3, the energy transference to the capacitor CM is finished and the diodeDM1is blocked. The energy transference to the output is maintained until the instantt4, when the power switch is turned ON.

5) Fifth Stage [t4−t5] (Fig.12): 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. The main theoretical waveforms of the modified SEPIC con verger with magnetic coupling and with the voltage multiplier at the secondary side are presented in Fig.13.The switch voltage and the voltage across all diodes is lower than the output voltage. The power switch turn-on occurs with almost zero current reducing significantly the switching losses. The current variation ratio (di/dt) presented by all diodes is limited due to the presence of the coupling inductor leakage inductance, reducing the negative effects of the diode reverse recovery current.

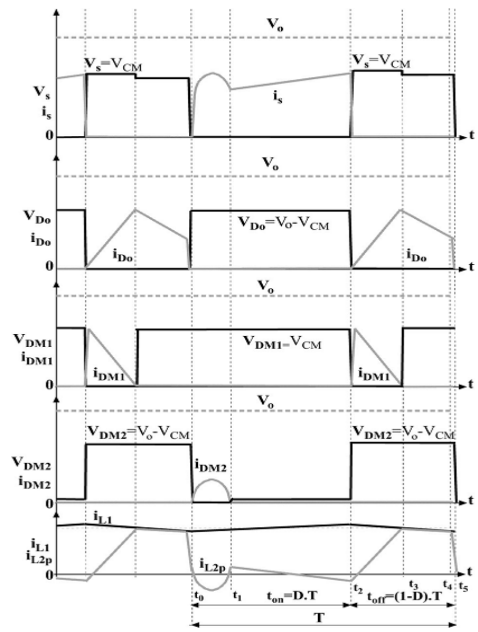

Fig.13. Main theoretical waveforms of the modified SEPIC converter with Magnetic coupling and voltage multiplier at the secondary side.

The static gain of the modified SEPIC converter with magnetic coupling and voltage multiplier is calculated by (8). The static gain can be increased by the windings turns ratio (n) without increasing the switch voltage

$$\frac{V_o}{V_i} = \frac{1}{1-D} \cdot (1+n) \tag{8}$$

Where the inductor windings turns ratio (n) is calculated by

$$n = \frac{N_{L2s}}{N_{L2p}}. \tag{9}$$

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VII.MATLAB/SIMULINK RESULTS

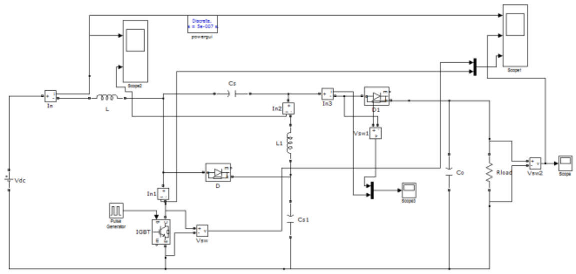

Fig.14.Matlab/Simulink Model of the Modified SEPIC Converter without Magnetic Coupling.

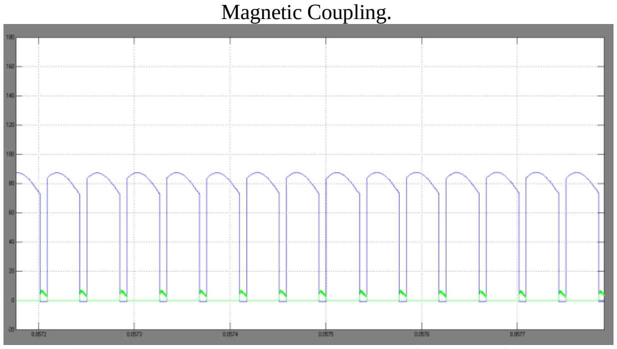

Fig.15. Output diode Do voltage and current of the modified SEPIC converter without magnetic coupling.

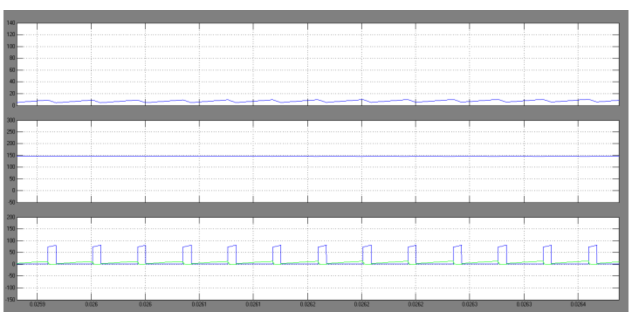

Fig.16. Input current, output voltage, switch current, and voltage of the modified SEPIC converter without magnetic coupling.

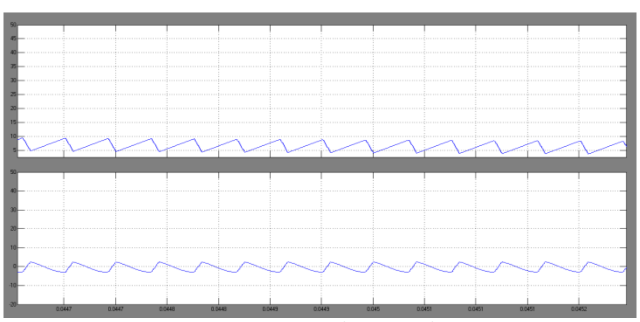

Fig.17. L1 and L2 inductor current of the modified SEPIC converter without magnetic coupling.

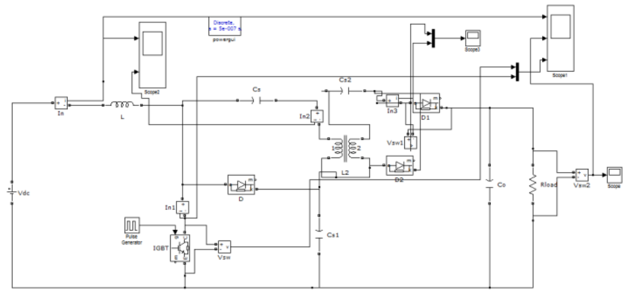

Fig18.Matlab/Simulink Model of The Modified SEPIC Converter With Magnetic Coupling.

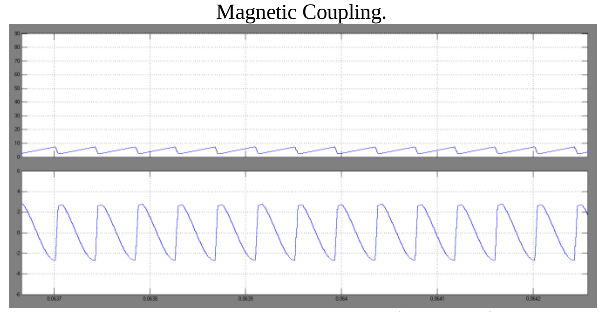

Fig.19. Switch current and switch voltage of the Modified SEPIC converter with magnetic coupling and voltage multiplier

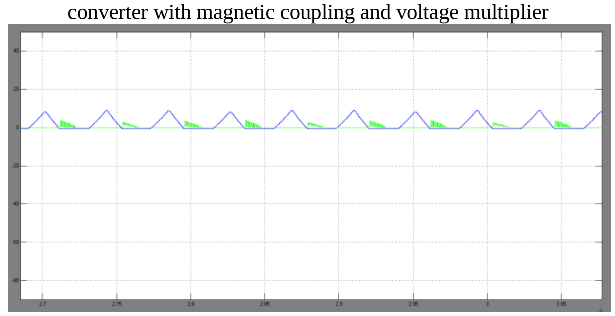

Fig.20. Output diode Do voltage and current of the modified SEPIC converter with magnetic coupling.

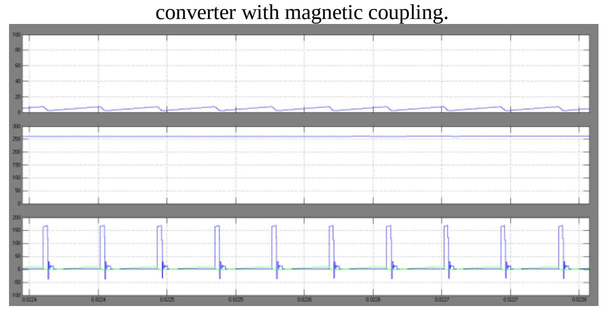

Fig.21. Input current, output voltage, switch current, and switch voltage of the modified SEPIC converter with magnetic coupling and voltage multiplier.

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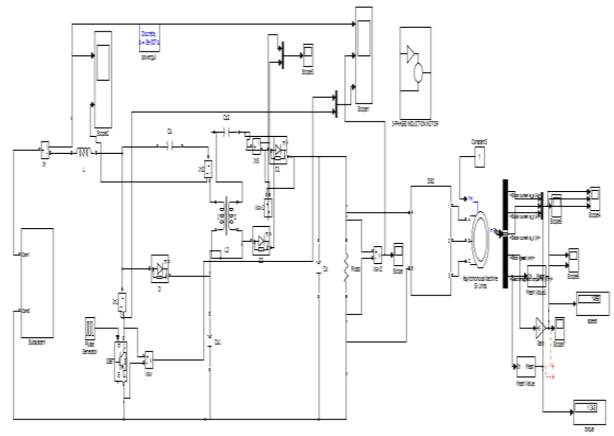

Fig.22.Matlab/Simulink Model Of The Modified SEPIC Converter With Magnetic Coupling And Induction Motor Drive.

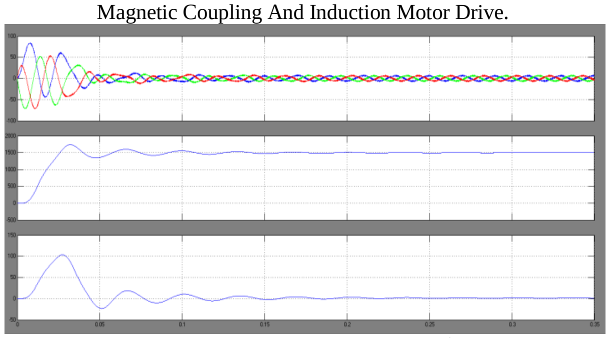

Fig.23 Current, Speed and Torque Characteristics of Induction Motor.

VIII. CONCLUSION

Two new topologies of non isolated high static gain converters are presented in this paper. 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 proposed converter of the structure with magnetic coupling can operate with static gain higher than 20 maintaining low the switch voltage and with induction motor drive. The response of the mechanics is to observer the speed torque characteristics.

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