Novel Design of Multiple-Input Single-Output DC-DC Converter

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***Abstract*— This paper presents the Novel design of Multiple-Input Single-Output (MISO) dc-dc converter. The main purpose of the converter is to allow connection of multiple power sources to a single dc bus system. Design and modeling of the MISO converter will first be discussed. Results of the computer simulation will be presented which demonstrate the ability of the converter to accept multiple dc sources while outputting only one dc voltage.**

Keywords-converter, dc system, power electronics

I. INTRODUCTION

Recently, DC based local distributed power systems have become more attractive due to the increase use of renewable energy sources. DC has several advantages over its AC counterparts. According to [1], the cost to setup a DC power system is cheaper when the overhead line distance is less than 500 miles. Also, DC line requires smaller towers so less space is needed to setup. The simplicity of connection simplifies the power system architecture in local area. Moreover, there is no alternating magnetic field around conductor, so inductive and capacitive effects do not exist. Inductance of transmission line is zero and capacitance exists between conductors is open circuit for DC, so only real power is transmitted. Since power factor is always unity, reactance compensation is longer necessary. Therefore, both power transfer capacity of the line and the efficiency of the system are higher. The frequency is always zero in DC supply; thus, no synchronous procedure is required to connect two DC power systems. This provides the ease to increase the system power when the demand is large. In addition, DC power flow is independent from the load and is controllable by adjusting the delay angles at the terminals.

Advantages of using DC power system especially for local distribution had brought us to the idea of establishing a DC house for areas unreachable by the power grid [2]. These areas do not have tall buildings to block the sun light and wind flow; therefore, these renewable energy sources can be harvested to the fullest. Also, villages near rivers can also take advantage to utilize hydro power as another DC power source. These DC bared PV panel, hydro-turbine and wind turbine can then be connected to an individual home. To extent the network, each individual home can also be connected in parallel to a single larger DC bus. This way, when there is a high demand of load in one home, the extra power can be easily fulfilled from the neighbors on the same DC bus. With a common DC bus, other DC sources can be tapped as another source of input power. In [3], power bike station has been installed in primary school as an enhanced power source for a Photovoltaic (PV) system. The power generated by the proposed station is proven to reduce 3 liters consumption per diesel fuel generator in every week. However, to collect the energy from these sources using DC, a DC-DC converter is needed to convert power directly from the renewable sources to the desire voltage for the DC bus. This DC-DC converter must be designed to be efficient for the viability of DC home. At the end, by having a reliable and efficient DC house system, our dependence on the power grid could be eliminated and in turn DC house may eventually provide electricity for people living in remote areas.

Researches have been conducted on methods to maximize energy collection from renewable sources. Maximum Power Point Tracking (MPPT) is one common technique used in PV system to maximize the input power to the converter. In [4], MPPT is applied to control PV panels in a photovoltaic system. In [5], mirror is used as reflector to increase the solar intensity of the solar panel. This method ensures maximum amount of direct normal sunlight to the solar panel. Experimental results presented in the same paper show that the system outputs more power by using reflectors and tracker. In [6], a hybrid wind power system is simulated to run in isolated areas. The system also includes a diesel generator to supply power synchronously with the wind turbine during high demand of load and batteries to store the redundant wind power. In [7], a hydro home system has been built and demonstrated in Nepal, where electricity is unavailable. The proposed system uses a motor dynamo to convert the kinetic energy of running water from a water tank to electricity. Power generated by the system is DC power which can be used to charge batteries and power up light and radio directly.

All studies mentioned well met their proposed applications. However, they are optimized only for a single renewable source and most of them are connected to the power grid or generators as auxiliary backup power source. Most isolated areas lack the supply from power grid and so dependence on one renewable source is not a reliable method. Gathering energies from all kinds of available renewable resources to generate electricity seem to be the more viable solution. This calls for the use of Multiple-Input Single-Output (MISO) DC-DC converter. A lot of interests have been poured into MISO converter in recent years. In [8], six well-known DC-DC topologies have been researched to determine which is feasible to be modified as multiple-input power converter. The paper identifies some assumptions and introduces certain rules which are useful to define the characteristics of MISO. However, the study focuses mainly on non-isolated DC -DC conversion which is not applicable in our case. In [9] and [10], MISO is used to integrate all renewable energy sources into a DC bus. AC grid or DC battery is also connected to the converter to store excess power from the sources or deliver power to the load. In [11] to [13], different kinds of isolated topologies have been investigated for renewable energy system.

In this paper, the design, modeling, an d simulation of MISO converter to provide an interface from multiple DC sources to a single DC bus output shown in Figure 1 is presented. The converter is designed to take in three dc sources and to output one voltage with low voltage ripple and tight line and load regulations while maintaining high efficiency. Operation and performance of the MISO converter will be confirmed by computer simulations.

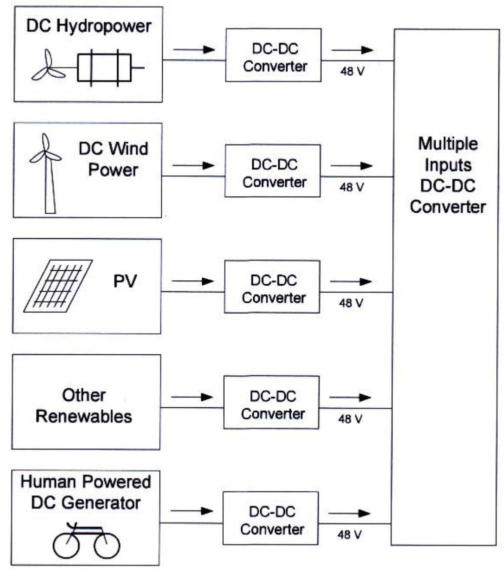

Fig 1. Multiple – Input DC-DC Converter

II. DESIGN SPECIFICATIONS

The overall system efficiency of the converter is considered as a whole; therefore, not only the suggested DC-DC converter but also components in the system need to be optimized to yield the most efficient operating voltage. Previous work has found that for maximum overall efficiency, the MISO converter must accept 24V input voltage. For the initial model, three renewable sources will be employed each with a maximum of 200W. Hence, the total maximum input power of MISO converter is 600W. Major loads comprise of low power devices such as laptop, television and LED light. Another assumption is that these devices are specified to operate at 48V input voltage in order to achieve the highest efficiency. This determines the required output of MISO converter which is to a maximum power of 350W at 48V.

Reliability of this converter is critical for home application. Since the peak input power is rated at 600W, it requires primary to secondary isolation to protect the user from touching to the sources by accident. This isolation can be achieved by using a transformer to step up the input voltage; thus, the converter design should be based on isolated topology.

The converter is expected to operate at 70% efficiency under full load. In order to ensure the quality of the output voltage, output voltage peak to peak ripple should be less than 2% of specified 48V output at full load and nominal 24V input. Line and load regulations are also targeted to be less than 3%. Table I summarizes the design requirements for the MISO dc-dc converter.

TABLE I. DESIGN REQUIREMENTS

Number of input source	3
Input source voltage	24V
Maximum output wattage	350W
Output voltage	48V
Line regulation	$\leq 3\%$
Load regulation	$\leq 3\%$
Output voltage ripple	$\leq 2\%$
Efficiency	$\geq 70\%$

III. DESIGN CONSIDERATIONS

After comparing with other isolated topologies, the full bridge topology as shown in Figure 2 was chosen due to its inherent advantages. For example, full bridge transformer requires only one single primary winding for each input source. Since the MISO converter has three renewable sources, full bridge transformer requires only three primary windings in total which occupy less winding area and thus minimize the transformer size. Also, when all four MOSFETs at the bridge in Figure 2 are switched off, energy is recovered via the body diode. Therefore, reset winding on the primary side can also be eliminated. Full bridge transformer is relatively smaller and requires less space for the same amount of output power.

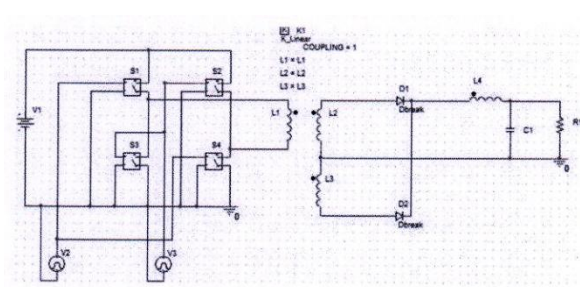

Fig 2. Power stage of full- bridge converter

Full-bridge converter delivers power to the output during both positive and negative switching cycle; hence, all four quadrants of the transformer's BH loop are used. In one cycle of operation under steady state condition, core's flux density swings up to +B and returns back to –B in the hysteresis loop of the ferrite core material. This avoids core's flux imbalance which drifts off the center of the hysteresis loop towards Saturation region. Also, when two diagonal MOSFETs are turned on, the maximum voltage stress across the other two MOSFETs is limited to the supply voltage. This maximum voltage limiting feature avoids the use of snubber circuit thus minimizing clamped power loss across the switch.

On the secondary side, output is connected to two windings with a common center tapped connection. Two output rectifier diodes are connected in series in each winding and each diode conducts and rectify for half of a cycle. Since two rectified input pulses are sent to the transformer, the output voltage carries a frequency which is twice of the primary switching frequency. This yields higher ripple frequency which reduces the output voltage ripple and requires less filtering at the output. Also, since inductor is connected at the output stage, smaller capacitor is required at the output. In short, full bridge converter offers smaller in size and better output quality compared to other topologies which makes the topology the most favorable for the MISO converter.

Instead of connecting all renewable sources in parallel on a single DC bus, the addition of power can be performed inside the core of the transformer by the produced magnetic flux. According to Ampere's Law, the magneto motive force (MMF) around a closed loop path ℓc inside the transformer core equals the product of current times the number of turns.

$$MMF = (H1 + H2 + H3)\ \ell c = N1I1 + N2I2 + N3I3 \text{---} (1)$$

N1, N2 and N3 are the number of turns on each windings coupled to the primary side of the transformer. : H1, H2 and H3 are the magnetic field intensity produced by the primary winding currents I1, I2 and I3 from each of the renewable sources. Also, magnetic field intensity, magnetic permeability μ of the core material, magnetic flux φ, magnetic flux density B and the cross sectional area of the transformer core Ac are related as follow:

$$H = B / \mu \text{ --- } (2)$$
$$B = \varphi / Ac \text{ --- } (3)$$

From (2) and (3), MMF can be related to magnetic flux by:

$$MMF = (\varphi 1 + \varphi 2 + \varphi 3)\ \ell c / (\mu Ac) \text{ --- (4)}$$

From (4), total magnetic flux linking inside the transformer core is the sum of magnetic flux φ 1, φ 2 and φ 3 produced by primary winding currents from each renewable source. According to Lenz' law, an induced voltage is formed on the secondary side of the transformer which produces current that would cause a flux opposing the original flux change. As a result, secondary side output current is related to the summation of total magnetic flux generated by primary winding currents. Since the output voltages of each renewable source are regulated to 24V, all primary windings in the transformer share the same number of turns. Output voltage can be adjusted by the turn ratio of primary and secondary windings. The proposed multiple primary windings transformer is depicted in figure 3.

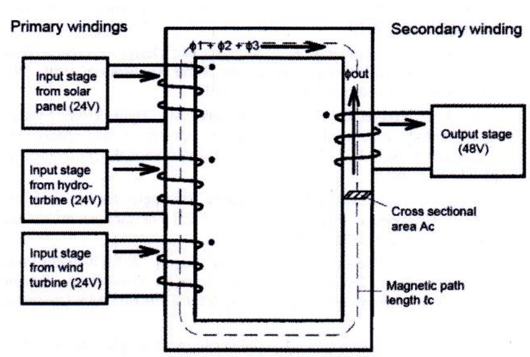

Fig 3. Diagram of MISO transformer

For the DC house application, the transformer is designed to operate for a temperature rise of 50°C. A commercially available ferrite core is used for the transformer core. The minimum primary turns can be determined by using Faraday's Law,

$$Np = ((V*t) / (\Delta B* Ae) \text{ --- (5)}$$

where

Np = minimum primary turns

V = DC voltage – 2 * V drop by Rds(on) of two MOSFET

ΔB = maximum flux density

Ae = minimum cross sectional area of core

t = duration of changing flux

The switching frequency is set to 200 kHz for the MISO; however, core flux swings at half of the switching frequency. Therefore, the transformer switching frequency is half of the switching frequency. Using "Core loss vs. Flux density" curve, the peak flux density is approximately 1200 Gauss. To prevent the core drives too close to saturation, 600 Gauss will be used in the transformer design. Also, maximum duty cycle is set to 80% of the maximum on time. Hence:

Np = ((24 V-2 V) * (0.8 * 4.878μs /2) * 108)/(1.96 cm2 *2*
600 Gauss = 1.825 turns ≈ 2 turns ----- (6)

Output voltage can be determined by using

$$Vo = Vin * (Ns/ Np) * D \text{ ---- (7)}$$

Since output is 48V, the number of secondary turns is:

$$Ns = (Vo/(Vin*D))*Np = (48/(24 * 0.8))*2 = 5 \text{ turns --- (8)}$$

In order to reduce proximity effect between primary and secondary windings of the transformer, the windings are constructed in sandwich winding pattern as depicted in Figure 4 to achieve high efficiency.

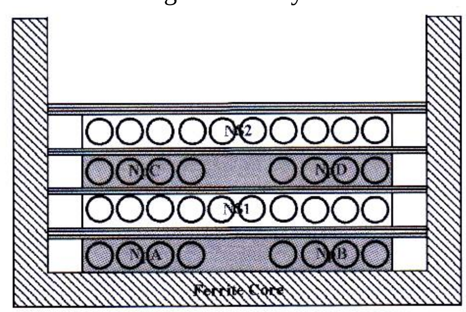

Fig 4. Sandwich pattern of MISO transformer

In Figure 4, NpA, NpB, NpC and NpD are the primary windings connected to the input sources. Ns1 and Ns2 are connected in parallel to the output rectifiers. According to equations (6) and (8), the ratio Np:Ns is 2:5. In the transformer, 4 turns are used in each primary winding and 10 turns are used in the secondary windings so as to maximize the winding space. The sandwich pattern Np/Ns/Np/Ns is used so that when all windings are loaded, the proximity effect between adjacent windings is minimized.

IV. SIMULATION RESULTS

To MISO converter was modeled and simulated using LTSpice. The schematic of the MISO converter showing just one of the converters is shown in Figure 5. LTC3723-1 PWM controller is used to drive the MOSFETs of the bridge. This controller features current mode control which uses resistive sensing on the primary side to control the maximum switch current. An error voltage across the sense resistor is used to compare with an internal 300mV nominal threshold. The PWM cycle stops once the threshold is exceeded. As a result, the four switches are protected from breaking down by over current fault. A 10 mΩ resistor is selected as the current sense resistance and the CS pin of the controller is tied to source 1 in the test setup.

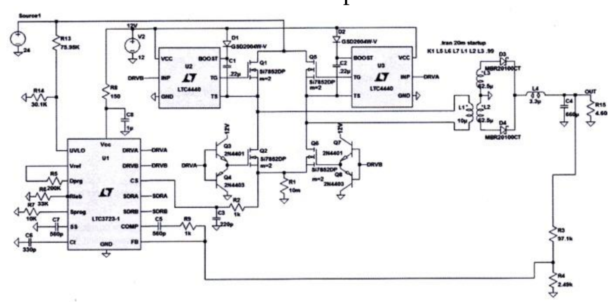

Fig 5. Sandwich pattern of MISO transformer

Since the proposed converter has three input sources, the gate signal needs to drive six MOSFETs for each half cycle. Signals to each bridge have to be synchronous; otherwise, two input sources will be shorted when one of the bridges is operating in positive half cycle while the other bridge is running in negative cycle. Three input sources can be controlled by three separate controllers; however, external frequency source is required to maintain the controllers in synchronous. Also, the PWM in each controller senses the feedback voltage from the output to adjust the duty cycle, so external logic circuit is needed to differentiate the feedback voltage to each controller. Instead of using three controllers, it can also be done using one controller. Since MOSFET drivers on the controller are designed to drive two switches on the bridge, Totem Pole is needed to boost the signal. In a totem pole output, two transistors are stacked one above the other and one transistor will be used in a common-emitter configuration while the other is used as an emitter follower. Drive signal is sent to the base of both transistors and the output of totem pole is supplied by the 12V source. Using totem pole to drive MOSFETs draws less current from the controller so that the same signal can be used to drive more MOSFETs. In Figure 5, totem pole is used to drive the low side MOSFETs while the high side MOSFETs are driven by the LTC4440 high side gate drivers.

Switching frequency is programmed by using a capacitor connected to the CT of the controller. Setting the switching frequency to 200 kHz, the capacitance needed is approximately 330 pF. Output inductor limits the amount of output current ripple and in the circuit a 3.3uH inductor is used at the output. To minimize the ESR, multiple capacitors can be connected in parallel at the output. In the actual circuit, two 330 μF are connected in parallel at the output so as to lower the power loss 481 from ESR.

The output voltage waveform resulted from the computer simulation shows that the converter produces 48 V output at full load as depicted in Figure 6. The peak to peak output voltage ripple at this condition is shown in Figure 7 and is measured to be (48.076 V – 47.9138) = 0.1622 Vpp. This translates to about 0.34% of the output voltage which is way below the 2% requirement. The inductor current waveform is shown in Figure 8 and indicates the continuous conduction mode of operation of the converter. The three currents coming from each of the three dc power supplies are shown in Figure 9. These waveforms proves that each power supply shares the total input current equally and hence shares the total input power since each power supply is assigned to be at 24 V.

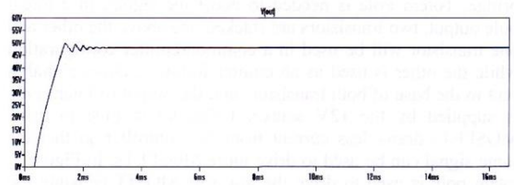

Fig 6. Output voltage waveform of the MISO converter

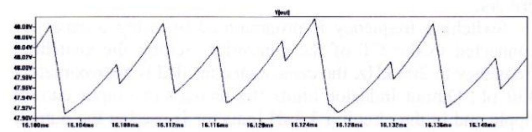

Fig 7. Peak to peak output voltage ripple

Fig 8.Output inductor current waveform

The average input current is measured to be 7.104 A. This gives overall MISO converter's efficiency of:

$$\eta = \frac{P_o}{P_{in}} = \frac{\left(\frac{48^2}{4.608}\right)}{(3)(7.104)(24)} = 97.75\%$$

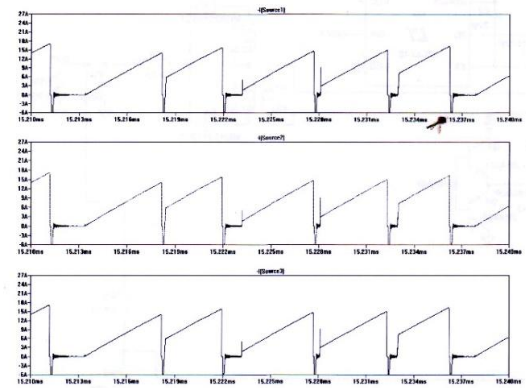

Fig 9. Input current waveforms

This efficiency number is high because the model does not incorporate real world losses. Figure 10 demonstrates the stability of the MISO converter in maintaining the nominal output when a step change is introduced at the load. The response time is observed to have very minimum amount of peak time and oscillates for about 1 ms before it reaches a steady state output.

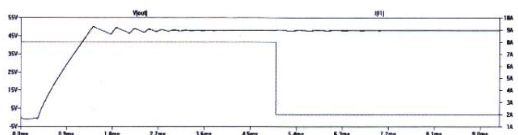

Fig 10. Step response of the output voltage

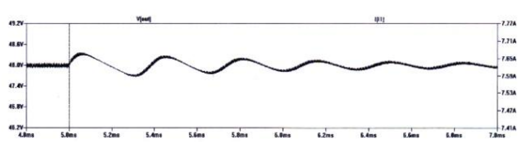

Fig 11. Transient response of output voltage

CONCLUSION

This paper discusses the design, modeling, and simulation of the Multiple-Input Single-Output dc-dc converter for use with multiple power sources supplying power to one common dc bus. Currently, the MISO converter is designed to interface three renewable energy sources to power a DC house. Simulation results exhibit the equal sharing capability of the MISO converter when drawing currents from three different dc power supplies. Moreover, the peak to peak output voltage ripple easily met the requirement with minimum amount of output capacitance. Overall, the MISO converter proves to be a viable solution for multiple input and single output applications.

Further work includes the addition of real world models of the components used to give a more accurate approximation of the converter's efficiency. Hardware development of the MISO converter is currently in progress whose results will be presented in the future conference.

REFERENCES

[1] Hanley, C.; Ross, M.; Foster, R.; Estrada, L.; Cisneros, G.; Rovero, C.; Ojinaga, L.; Verani, A., "Using renewable energy for rural connectivity and distance education in Latin America" Photovoltaic Specialists Conference, 2002.

[2] The DC House Project Website, http://www.calpoly.edu/~taufik/dchouse

[3] Krueasuk, W.; Poungchingyam, A.; Sriamonkitkul, W.; Intarajinda, R.; Bhasaputra, P.; Pattaraprakorn, W.; , "Powerbike to Enhance Hybrid PV-Diesel System for rural primary school" Energy and Sustainable Development: Issues and Strategies (ESD), 2010 Proceedings of the International Conference on , pp.1-7, 2010.

[4] Chen, Y.-M.; Liu, Y.-C.; Wu, F.-Y.; Wu, Y.-E., "Multi-Input Converter with Power Factor Correction and Maximum Power Point Tracking Features" Applied Power Electronics Conference and Exposition, 2002. APEC 2002. Seventeenth Annual IEEE, pp.490-496 vol 1, 2002 .

[5] Abd Malek, N.; Hasini, H.; Rahman, A.A.; Nasharuddin Mohd Jaafar, M., "An Improved Solar PV System for Malaysian Rural Electrification part I: Design and testing of solar PV with tracker and reflectors" Research and Development (SCOReD), 2010 IEEE Student Conference on, pp.452-457, 2010.

[6] Kathirvel, C.; Porkumaran, K , "Analysis and Design of Hybrid Wind- Diesel System with Energy Storage for Rural Application" IPEC, 2010 Conference Proceedings, pp.250-255, 2010.

[7] Anup, K.C.; Poudel, G.; Poudel, S.; Khadka, M., "Hydro Home System - an Inventory on Rural Electrification" Computer and Automation Engineering (ICCAE), 2010 The 2nd International Conference on, pp.338-341, 2010.

[8] Kwasinski, A., "Identification of Feasible Topologies for Multiple-Input DC–DC Converters" Power Electronics, IEEE Transactions on Volume: 24, Issue: 3, pp.851-861, 2009.

[9] Ting-Chia Ou; Whei-Min Lin; Cong-Hui Huang, "A Multi-Input Power Converter for Hybrid Renewable Energy Generation System" Sustainable Alternative Energy (SAE), 2009 IEEE PES/IAS Conference on , pp.1-9, 2009.

[10] Ruichen Zhao; Kwasinski, A., "Multiple-input single ended primary inductor converter (SEPIC) Converter for distributed generation applications" Energy Conversion Congress and Exposition, 2009. ECCE 2009. IEEE, pp.1847-1854, 2009.

[11] Dongsheng Yang; Xinbo Ruan; Yan Li; Fuxin Liu, "Multiple-input Full Bridge DC/DC Converter" Energy Conversion Congress and Exposition, 2009. ECCE 2009. IEEE , pp.2881-2888, 2009.

[12] Huang-Jen Chiu; Hsiu-Ming Huang; Li-Wei Lin; Ming-Hsiang Tseng, "A Multiple-Input DC-DC Converter for Renewable Energy Systems" Industrial Technology, 2005. ICIT 2005. IEEE International Conference on , pp.1304-1308, 2005.

[13] [Shengyong Liu; Xing Zhang; Haibin Guo; Jun Xie , "Multiport DC/DC Converter for stand-alone photovoltaic lighting system with battery storage" Electrical and Control Engineering (ICECE), 2010 International Conference on , pp.3894-3897, 2010.

[14] John Bottrill, "How to Specify the Current Sense Resistor in a Converter using the UCC28083" Texas Instruments Application Report SLUA584, pp.1-6, 2010.