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Development of A Direct Conductive Coupled Multi-Input Phase-Shifted Full-Bridge DC-DC Converter

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Abstract: Hybrid energy system is commonly employed in renewable energy systems to bridge the gap of non-availability of one power source with the others. In this work, a direct conductive electrical circuit connection topology for realizing multiple power source synchronization in the hybrid energy system is proposed. A three-input power sources integration scheme was realized via forward-conduction bidirectional blocking switch which serves input to the common power conversion stage of phase-shifted full-bridge DC-DC converter to boost the synchronized common bus voltage. An average current sharing controller is designed for the multiple parallel power sources to ensure equal load sharing when all the sources operates on the same and different voltage level. In this study, a 3-kW rating hybrid energy system was implemented in Simulink environment to investigate the multiple source integrator, the current sharing capability, and the common power conversion stage performance. The system ensured equal load sharing, allowed individual and simultaneous power transfer from the multiple sources to the load under the same and different operating supply voltage level.

Keywords: DC-DC converter, hybrid energy, multi-input converter, power interface, phase-shifted full-bridge.

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1. INTRODUCTION

Energy hybridization is a popular technological solution being exploited in bridging the gap of renewable generations non-availability and variability [1, 2]. A typical hybrid energy system (HES) comprised of two or more energy sources, power conditioning interface, and optional energy storage system [3]. The advantage of complementary operational mode that tackles non-availability and intermittency of one energy source with others is a major factor behind HES popularity and modern-day adoption. Primarily, HES are mostly designed to effectively utilize locally available resources to generate electricity for standalone or grid connected system.

Multiple power sources synchronization are achieved via the power electronics interface with configurations capable of accepting, integrating, operating power from diverse sources [4]. Presented in Figure 1 is a generalized hybrid energy system configuration with the power electronic interface between the source and the load. The interface scheme is responsible for input supply adaptation for direct connection to the utility grid or standalone consumer. The system comprised of the input source, the input converter module (DC-DC converter), an inverter module (DC-AC inverter), the output connection interface, and the controller unit. The multiple source integration scheme could be based on alternating current (AC) or direct current (DC) component dictated by the type of energy source or storage system.

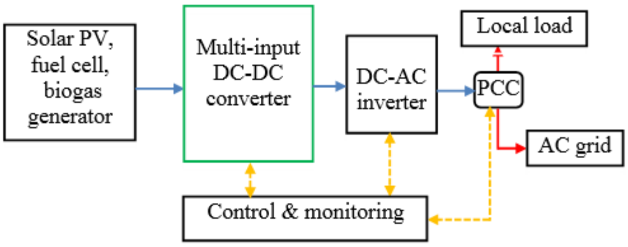

Figure. 1. Hybrid energy system with power electronic interface

The most common method used for multiple power sources integration in the hybrid energy system is the direct current (DC) coupling owing to the advantages of high power quality, high reliability, ease of control and expansion since it requires less synchronization effort [5]. The DC power source can be converted to AC directly or through two-stages where DC-DC converter is first used for the voltage regulation and boosting. The conventional approach for implementing a multi-input DC-DC power converter involves using strings of single-input-single-output converter units for individual energy source [6, 7]. The individual converter output is then connected to a common DC bus to serve the load. The system configuration naturally has a large number part, bulky, relatively complex with reduced overall system efficiency. The interest in modular design, lightweight, reduced size, cost, and high reliable motivate interest in the development of multi-input converter with one central control unit for a diverse energy source. The configuration comes with fewer component parts, less complexity, easy and centralized control, reduce size as well as high flexibility for a diverse choice of energy resources [8].

The two major possible means of connecting power source is either magnetically or conductively. In conductively connected system, one loop affects the neighboring loop through current conduction. While in the case where two loops with or without contacts affect each other through the magnetic field generated by one of them is said to be magnetically coupled. The direct conductive coupling methods for achieving multiple power source integration uses field effect transistor (FET) switching devices with active/passive component and the magnetic coupling techniques depends on magnetic field coupling from inductive elements.

Broad sets of conductive DC-DC converter topologies have been introduced in [9] for multi-input DC-DC converter application and further studies have shown that not all basic converter topologies are feasible for synthesizing multi-input converter. The popular topologies that found their application in synthesizing multi-input DC-DC converter include the buck-boost, buck-buck boost, buck-buck, and buck boost-buck boost converters. A dual-input single-output DC-DC converter based on buck-buck boost converter was investigated in [10] for hybrid energy system application. The topology allowed the load to draw power individually and simultaneously from the source. The proposed topology achieved power integration with fewer part counts, but deficiency is the number of input limitation which cannot be extended beyond two sources. The integrated buck-buck converter is another popular basic DC-DC converter topology widely used in energy hybridization [11]. The application and operation of buck-buck double input-single output converter have also been presented in [12, 13]. This class of multi-input converter has the capability of transferring power from input sources to the load individually and simultaneously under different operating modes.

Another common topology that found its application in the dual-input converter is integrated buck boost-buck boost converter [14, 15]. This topology does not support simultaneous energy transfer from dual energy sources to the load except one source at a time. The load draws power from each source when the corresponding series switch is in on-state and the other switch in off-state [15]. Aside from the dual input DC-DC converters, some literature has reported n-numbered multi-input DC-DC converters. Recently, Dobbs et al [16] and Khaligh et al [8] proposed topology for n-numbered multiple source converter. The topologies were based on buck-boost converter capable of interfacing diverse energy sources with different voltage-current characteristics to a common load while achieving a low part count.

Magnetic coupling technology has also been widely investigated for realizing multiple energy source synchronization. Multi-input DC-DC converters based on magnetic-coupling for a multi-input phase-shifted full bridge DC-DC converter has been reported in [17-19]. The multiple energy source integration was based on flux additivity using a winding coupled transformer with a common output-stage circuit. The input DC sources are combined in magnetic form by adding up the magnetic flux produced in the magnetic core of the coupled transformers. The converter topology can transfer power from the sources individually and simultaneously to the load. Magnetic coupling technique has advantages of accepting input voltage with the wide magnitude and offers flexibility for multiple input stage circuit by adding more windings, but all these are at the expense of increased cost and weight.

This paper presents the implementation and investigation of hybrid energy system with three inputs integrated via direct electrical circuit connection. The common power conversion stage employs phase-shifted full-bridge (PS-FB) DC-DC converter which was implemented in MATLAB/Simulink for investigating the dynamic performance of the proposed power source synchronization scheme. The results show that the integration scheme supported individual and simultaneous power transfer from the source to load. Also, the PS-FB converter performance was satisfactory as confirmed by the voltage-current dynamics of the system which includes the transformer voltage-current waveforms, the converter DC output voltage and current with 90 % overall system efficiency

2. METHODOLOGY

2.1 Hybrid Energy System

Power electronics interface is employed in hybrid energy systems for adapting power generations output voltage, current, and frequency to meet load or grid demand. The interface is used to achieve multiple power source synchronization, conversion and power transfer between the sources and the load. The backbone of the system is the control unit that monitors and regulates power flow for quantitative and qualitative power delivery. A simplified block diagram of a proposed multi-input DC coupled HES is presented in Figure 2 as a case study with three different unregulated DC power sources. The common power conversion stage is based on PS-FB ZVS DC-DC converter that provided a regulated 400V DC output voltage from the multiple 48V DC sources.

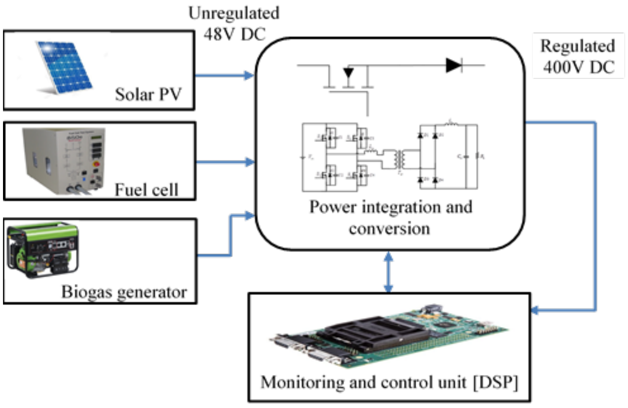

Figure 2. Proposed hybrid energy system

The input stage of the hybrid energy system comprised of unregulated DC sources namely; solar PV, fuel cell, and DC biogas generator synchronized to a common DC bus via direct conductive electrical connection. The common power conversion stage of the system employs PS-FB DC-DC converter owing to the advantage of high-power handling capability and low switching losses for improved efficiency. The synchronized input sources provide a common 48 V nominal voltage to the PS-FB DC-DC converter which is boosted to 400V DC output voltage. A PID controller was designed for the multiple power sources integration stage in order to ensure equal load sharing, most especially under different sources operating voltage condition. In this work, a 3kW converter was designed with 100 kHz operating switching frequency to reduce the size of the required isolated transformer for the voltage step up function.

2.2 Multiple Power Source Integration Circuit

This section presents the proposed direct conductive electrical connection topology for multiple power sources synchronization and the common power conversion stage. The output power from different renewable energy sources is first synchronized to produce common output voltage level using current sharing controller based on their capacity ratings. The next stage is the power converter stage to achieve the require voltage level which was realized by adopting zero voltage switching phase-shifted full bridge DC-DC converter.

The synchronization configuration block diagram is presented in Figure 3 comprising of multiple power sources integration stage to achieve common output voltage. The integration architecture has the capability for n-input which provides for power source flexibility with a single point of common output connection via the DC bus. The three input DC power sources are synthesized using parallel connected pulsating current source cells (PCSs) realized from bi-directional voltage blocking capability of MOSFET when combined with series reverse blocking diode. This configuration allows MOSFET to be operated as current sources making it possible to connect multiple energy sources with same and different voltage characteristics in parallel. The MOSFET switch provided isolation for each input source for engagement and disengagement based on specified operating input voltage range and the combined source voltage is smoothened by a DC filter capacitor prior to serving input to the H-bridge inverter. The current contribution from each source depends on the voltage and the path resistance and the system allowed individual and simultaneous power transfer from sources to the load.

The circuit diagram of the common power conversion stage based on PS-FB DC-DC converter is presented in Figure 4. The converter steady-state analysis and mathematical derivation for the circuit elements parameters have been provided in [20] and the specification of a 3-kW rating used in this study is presented in Table 1. The converter was designed to operate in continuous conduction mode with 1.5A ripple current and minimum ZVS range between 40% load to the full load current. The output bridge rectifier stage converts the transformer secondary AC to 400 V DC with ripples which were filtered by employing low-pass filter comprising of inductor and capacitor (LC-filter). The converter load was modelled as a resistor (RL) with a resistive value of 53.33 Ω under full load current.

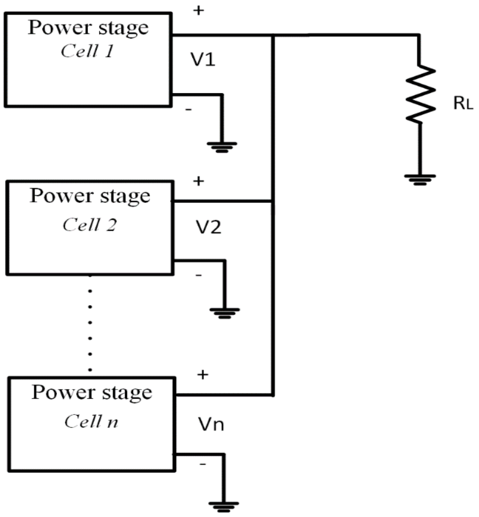

Figure 3. Parallel power source cofiguration

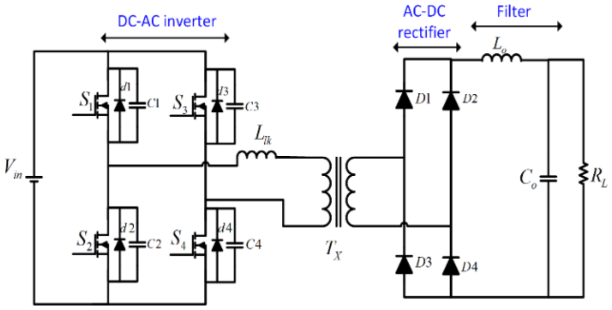

Figure 4. Full-bridge DC-DC converter topology

Table 1. Full bridge DC-DC converter specification

Parameters	Values
Input voltage (v)	48
Output voltage (v)	400
Ripple voltage (V)	1
Averaged output current (A)	7.5
Ripple current (A))	1.5
Switching frequency (kHz)	100
Transformer turn ratio	1: 14
Efficiency (%)	>90

2.3 Current Sharing Controller Design

The interconnection of multiple power sources in parallel does not guarantee load current sharing and good voltage regulation among the sources. Practically, there is no two-power source that have same internal resistance or line impedance even though with same voltage magnitude. A little millivolt difference can lead to load sharing imbalance among the source with the source having higher voltage supplying load current to its rating capacity. In order to achieve equal load sharing among the multiple parallel power sources in this work, a load current sharing control was based on average current sharing scheme was incorporated as presented in Figure 5.

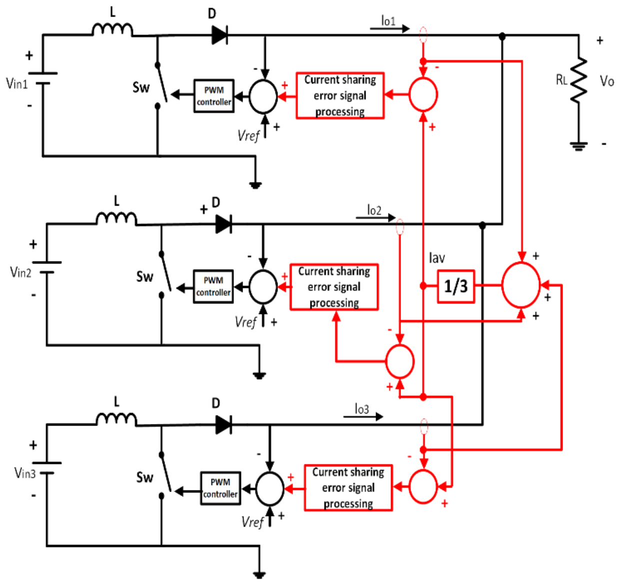

Figure 5. Parallel power sources with current sharing control

The average current sharing mode was developed for the input stage current sharing control and a proportional-integral (PI) controller were designed to regulate the sources current sharing error for equal load balancing. The load current sharing control scheme comprised of both current control loop and voltage regulator. The output current from each source are sensed and the averaged computed current served as reference current to the sources as shown in Figure 5. The amplified current sharing error signal is then compared with the reference voltage which feeds the PWM generator to each of the power source to produce the desired current sharing.

The PI controller parameters for current error signal processing were obtained by trial-and-error method with P term setting of 0.011 and the I term setting of 1. The multiple energy source integration was implemented in MATLAB/Simulink environment as presented in Figure 6 for investigating the system performance on active load sharing and power transfer from the sources to the load. Since the proposed energy sources are renewables characterised by varying output generation, controlled voltage source was used to mimic the variable voltage source feature. In the Simulink model, the stair generator tool block was configured to generate a variable voltage that characteristics the input sources.

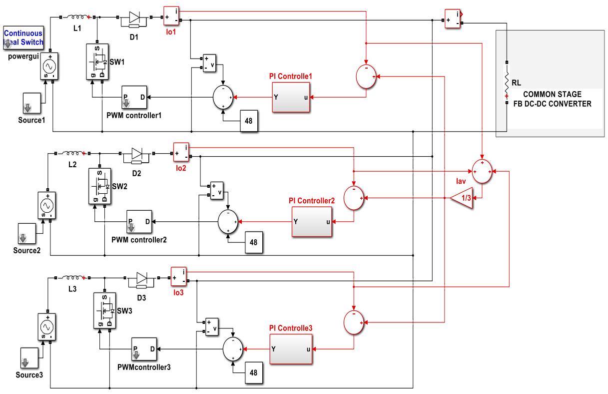

Figure 6. Power source synchronization with current sharing control

3. RESULTS AND DISCUSSION

2.1 Multi Power Sources Integration Evaluation

The developed multi-input power sources integration scheme for HES application has three distributed energy resources synchronized to a common DC bus. The operating performance of the designed direct circuit connection was investigated for equal load current sharing among the sources while operating under same and different input voltage. The results of the power source integrator when the three sources were operated under nominal input voltage is presented in Figure 7. Each of the input sources *Vin1, Vin2, and Vin3* supplies 48V nominal voltage. Figure 8 shows the current (Io)contribution of each source to the total load current demand for the 3kW rating system. It was observed that each source supplied an average current of 21A totaling 63A from when the three-power source were operated under same voltage level. The synchronized output voltage (*Vdc*) of the three power sources is presented in Figure 9 and this serves input to the full bridge DC-DC converter.

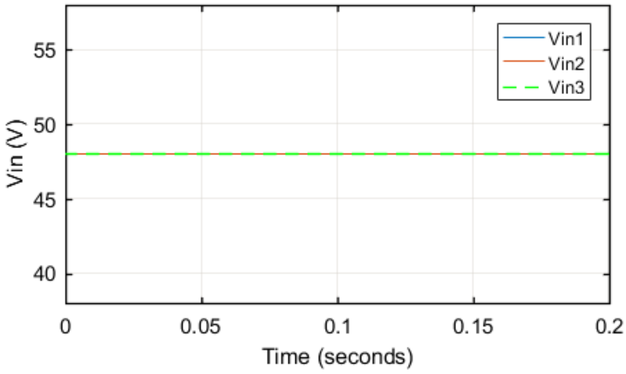

Figure 7. Multiple power sources with same voltage level

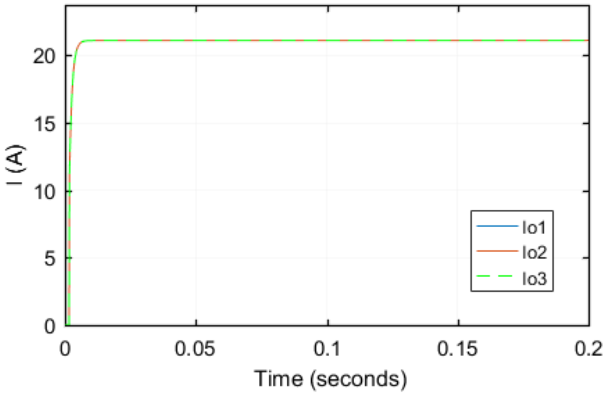

Figure 8. Multiple power sources current sharing with same voltage level

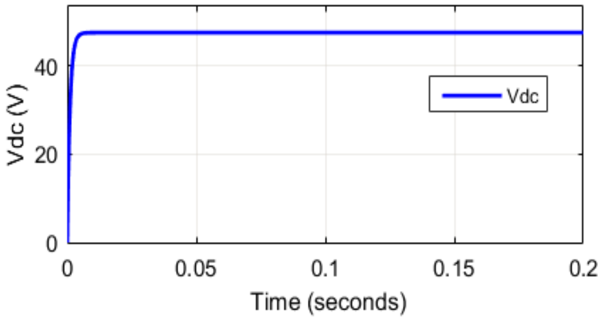

Figure 9. Synchronised common output voltage

The test result of the power integration scheme when the three power sources are operated under different input voltages is presented in Figure 10. The power source 1 (*Vin1*) supply voltage is set to 36V, source 2 (*Vin2*) is set to 40V and source 3 (*Vin3*) is set to 48V as shown in the Figure 9 voltage waveforms. The current contribution from the three power sources are presented in Figure 11 showing both transient and steady state current sharing among the three power sources. At start up, the source Vin3 with highest voltage value supplies more than 50A current before the current sharing controller action forced equal current contribution from the remaining two power sources. The power source integrator with the current sharing control comfortably achieved 21A steady state load current sharing among the three sources with different voltage level. The synchronized output voltage (*Vdc*) of the three-parallel source is also presented in same Figure 12, having 48V amplitude as dictated by the source with highest voltage value.

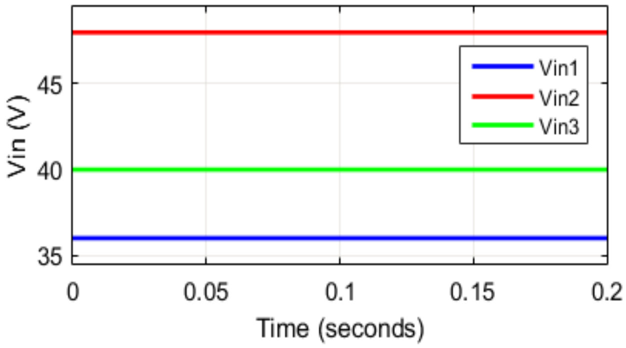

Figure 10. Multiple power sources with different voltage level

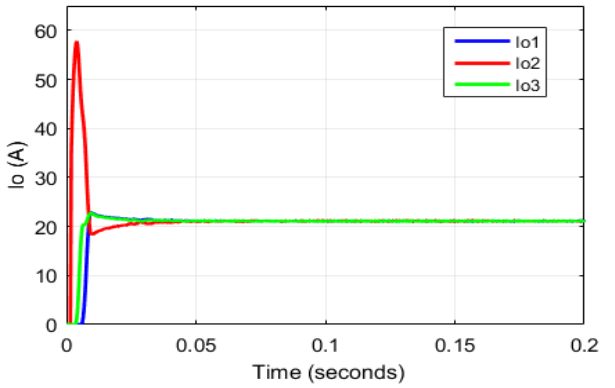

Figure 11. Multiple power source current sharing with different voltage level

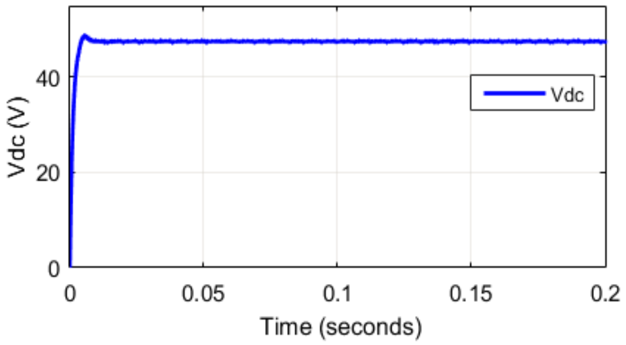

Figure 12. Synchronised common output voltage

2.2 PS-FB ZVS DC-DC converter Performance

The main function of the PS-FB ZVS DC-DC converter was to boost the 48V synchronized output voltage of the power integrator to 400V. The dynamic performance of the converter was investigated under full rated load current of 7.5 A and the circuit waveforms are presented in Figures 13, 14 and 15. The scaled inverter voltage, transformer primary voltage and current waveforms for a complete switching cycle are shown in Figure 13. The inverter voltage switches between $+V_{dc}$ and $-V_{dc}$ for each half cycle. In the first half cycle, when switches S_1 and S_4 are in *on*-state, the inverter voltage rises to reach the supply voltage +48 V in the positive direction and later return to 0 V during the freewheel stages. In the second half switching cycle, the switch S_2 and S_3 are in *on*-state with ZVS transition and the inverter voltage rise to -48 V in the negative direction.

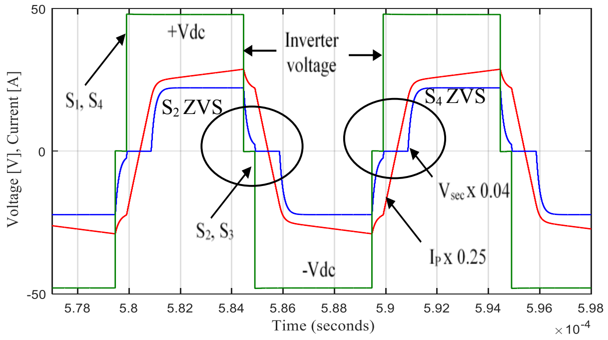

Figure 13. Inverter voltage, transformer primary current, and secondary voltage

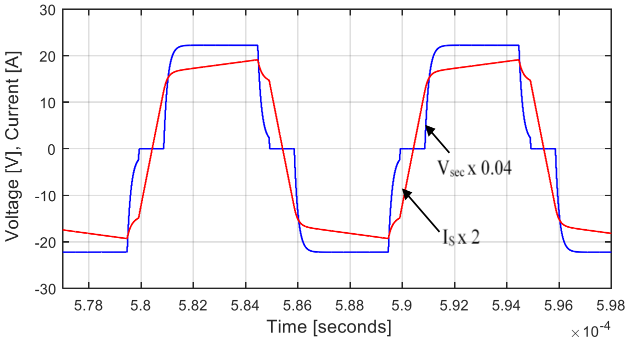

Figure 14. Transformer secondary voltage and current

As observed in Figure 13, the transformer primary current (I_P) flows in the positive direction during first half switching cycle rising with a slope of V_{in} / L_{lk}, following the freewheel mode. When switches S_1 and S_4 are in *on*-state, the primary current rise to reach reflected output inductor current (nL_o) during the power delivery mode. Following power delivery mode, the switching cycle enters the freewheel mode and the current flow changed to the negative direction and rises with a slope V_{in} / L_{lk}. During the second stage power delivery mode when switches S_2 and S_3 are in *on*-state, the primary current rise to reach reflected output inductor current (nL_o) to complete a switching cycle.

The transformer secondary voltage and current in Figure 14 follow the same switching pattern as the primary side, alternating between the positive and negative plane in each half switching cycle. The transformer steps up action have reflected on the secondary voltage and current by a factor of transformer turn ratio in which the secondary voltage is now $n.V_{dc}$ and secondary current is $(1/n)\, I_P$ as dictated by the load current demand. The inductor loads current (i_L) was designed for 1.5 A ripple in continuous conduction mode and the load current has minimum and maximum peak current of 6.85 A and 8.18 A respectively as observed in Figure 15 with an average peak load current of 7.5 A.

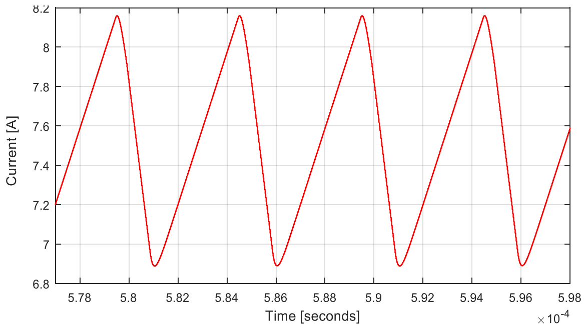

Figure 15. Inductor load current

The converter efficiency under different load condition is presented in Figure 16. The converter efficiency test was carried out for load span between 15 % to the full rated load current. The input-output power for 15 %, 40 %, 60 %, 80 % and 100 % load current were measured and used for the system efficiency computation. It was observed that the system efficiency between 40 % to 100 % load current is almost linear for the soft switching region of the DC-DC converter

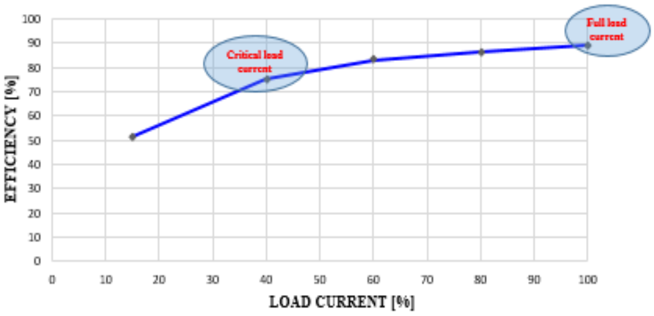

Figure 16. Converter efficiency against load current

4. CONCLUSION

A multiple power source integrated scheme based has been designed and investigated in MATLAB/Simulink environment. The parallel input sources synchronization based on direct conductive electrical circuit connection performed satisfactorily as the proposed techniques supported equal load current sharing among the multiple power sources, individual and simultaneous power transfer from the sources to the load. The operational voltage-current waveforms and high conversion efficiency of the common power conversion stage based on PS-FB ZVS DC-DC confirmed the system smooth operation for quantitative and quality power delivery. The proposed multi-input power interface demonstrated good potential for application in hybrid energy systems. This scheme will support bridging the gap of non-availability of one energy source with the others in hybrid energy systems since the system allowed individual and simultaneous power transfer from the sources to the load.

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