A New Bidirectional Isolated Converter for Grid Connection

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***Abstract* -- This paper proposes a bidirectional isolated AC-AC converter for grid connection of various loads or energy sources. The converters can be utilized for interfacing renewable energy sources to the grid as well as traditional motor drives. It does not employ any line-frequency transformer, large electrolytic capacitors, and inductors to diminish the volume and enhance the reliability of the converter. Instead, it uses high-frequency transformers and small film capacitors. Also, Because of its modular structure, it can be extended easily according to the system voltage. Its configuration and the concept of power flow are introduced and the simulation results are presented.**

***Index Terms*—AC-AC power converter, Bidirectional power flow, HF transformer, Grid connection**

I. INTRODUCTION

The proportion of renewable energy sources, such as photovoltaic and wind energy system, in the conventional grid is in a growing trend. However, because the renewable power has its inherent variation in terms of its voltage and/or frequency, it can not be connected to the grid directly. In order to interface the renewable sources to the grid, a suitable power converter is required. As the demand of the renewable sources increases, many researches have been performed regarding this topic [1]-[3].

Several topologies employ a line-frequency transformer and a PWM boost rectifier to link the renewable sources to the grid [1]. However, the line-frequency transformer and large inductor would increase the system size. Beside, electrolytic capacitors at DC-link deteriorate the reliability of the system owing to its short life expectancy. Some other studies have been performed to utilize a high-frequency transformer instead of the line-frequency transformer [2], [3]. However, they still need large input inductor to operate the boost converter for grid connection. And because each phase of the AC system is totally isolated, large electrolytic capacitors are required to buffer the power fluctuation of single phase.

This paper proposes Series-connected Universal Link converter (SUL converter) for grid connection of various loads or energy sources. The converter is capable of bidirectional power flow and power factor control. And the size of the converter can be reduced because it does not require large reactive components such as large inductors, electrolytic capacitors, and line frequency transformers. Without the PWM boost converter, the current waveform to the grid can be kept as sinusoidal one. Also, because it has modular architecture, by properly configuring the modules, the converter can be connected to the various voltage levels. Its configuration and the concept of power flow are introduced and the simulation results are presented..

II. STRUCTURE OF THE SUL CONVERTER

Fig. 1 shows a basic structure of SUL converter. It has one grid-connected input port and one three-phase output port, and it is consisted of H-bridge modules. Each input/output port consists of H-bridge modules and each modules of same phase is connected in series across the stages. The number of stage is decided depending on the DC-link voltage of one H-bridge module and input AC voltage. As the interface of the ports is made via modular architecture, the converter can be extended universally.

The H-bridges configuring the proposed converter is classified into four types according to their operations. Low-frequency bidirectional rectifier, sine-modulated full bridge inverter, high-frequency bidirectional rectifier, and output full bridge inverter are them.

The low-frequency bidirectional rectifier is configured similar to the electrolytic capacitor-less inverter [4]. It acts as a bidirectional AC-DC interface with no large passive elements, such as bulky DC-link capacitor or heavy input inductor, except small snubber capacitors and filter circuit. Using only small capacitors at the DC-link, the input currents can be kept as sinusoidal without chopping the phase voltages.

The filter capacitors help distributing the phase voltage evenly across the stages. They also function as input filter along with line inductance; additional small inductors might be required to tune the input filters. The switches of the low-frequency bidirectional rectifier are switched synchronously to the line-frequency; hence their switching losses are negligible.

The sine-modulated full bridge inverter and the high-frequency bidirectional rectifier are connected to the high-frequency multi-winding transformer. They perform isolated, bidirectional power conversion analogous to conventional isolated DC-DC converters [5].

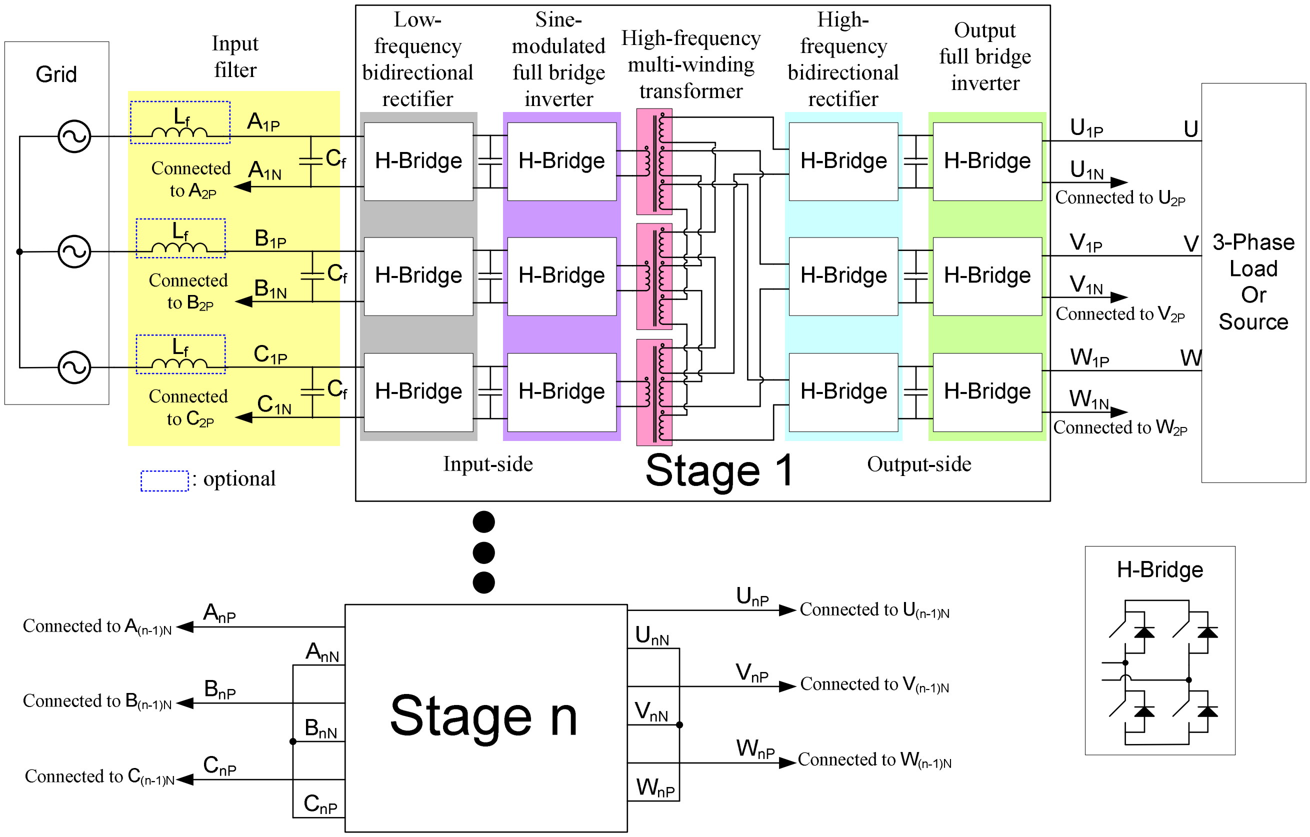


Fig. 1. Circuit diagram of proposed series-connected universal link AC-AC converter

The galvanic isolation between the input and output port is achieved with the transformers. The switching frequency of H-bridges in this part can be set at around ten kilo Hertz. Therefore, the size of the transformer used in this converter is much smaller than that of conventional line frequency transformers used in other topologies [1].

The transformer has one winding on the primary side and multi-windings on the secondary side. The number of windings on the secondary side is determined by the number of phases of the output-side. Because of the series connection of each secondary winding of the transformer, the average voltage applied on the high-frequency bidirectional rectifier can be constant and the total power transferred through one transformer become constant when the loads are balanced.

The DC outputs of the high-frequency bidirectional rectifier provide isolated DC voltage sources. Using them, the output full bridge inverter acts like a single cell of a cascaded multi-level inverter [6].

III. POWER FLOW CONCEPT

The SUL converter has a sinusoidal form of the input currents without PWM boost converter. This section demonstrates how it is achieved. At first, the input phase voltage can be defined as follows,

$$\begin{aligned} v_{phase\_a} &= V\sin\left(\omega t\right), \\ v_{phase\_b} &= V\sin\left(\omega t-\frac{2}{3}\pi\right), \\ v_{phase\_c} &= V\sin\left(\omega t+\frac{2}{3}\pi\right), \end{aligned} \tag{1}$$

where V is the magnitude of the phase voltage and ω is the angular frequency of the grid.

The switches of low-frequency bidirectional rectifier turn on when their anti-parallel diodes turns on. Then, the DC-link voltages of the input-side become absolute value of input phase voltage. These voltages can be derived as follows,

$$\begin{aligned} v_{dc\_a} &= V\left|\sin\left(\omega t\right)\right|, \\ v_{dc\_b} &= V\left|\sin\left(\omega t-\frac{2}{3}\pi\right)\right|, \\ v_{dc\_c} &= V\left|\sin\left(\omega t+\frac{2}{3}\pi\right)\right|. \end{aligned} \tag{2}$$

With these DC-link voltages, the sine-modulated full bridge inverter synthesizes their output voltages as follows,

$$
\begin{aligned}
v_{ac\_a} &= mV\left|\sin\left(\omega t\right)\right| sign\left(\sin\left(\omega t\right)\right) \\
&\quad \sin\left(\omega t-\varphi\right) square(t), \\
v_{ac\_b} &= mV\left|\sin\left(\omega t-\frac{2}{3}\pi\right)\right| sign\left(\sin\left(\omega t-\frac{2}{3}\pi\right)\right) \\
&\quad \sin\left(\omega t-\frac{2}{3}\pi-\varphi\right) square(t), \\
v_{ac\_c} &= mV\left|\sin\left(\omega t+\frac{2}{3}\pi\right)\right| sign\left(\sin\left(\omega t+\frac{2}{3}\pi\right)\right) \\
&\quad \sin\left(\omega t+\frac{2}{3}\pi-\varphi\right) square(t),
\end{aligned}
\tag{3}
$$

where m is the modulation index($0 \le m \le 1$), *square(t)* is the modulation function alternating between -1 and 1 with the switching frequency of the PWM, *sign(x)* is 1 when x is positive and -1 when x is negative, and φ is the desired displacement power factor angle defined as the angle between the phase input voltage and current.

These output voltages are applied to the primary side of the transformers. Because the secondary windings of the transformer are connected in series, the voltages applied on the high-frequency bidirectional rectifier are sum of (3), which can be derived as follow,

$$
\begin{aligned}
v_{syn} &= v_{ac\_a} + v_{ac\_b} + v_{ac\_c} \\
&= \frac{3}{2} mnV\cos\left(\phi\right) square(t),
\end{aligned}
\tag{4}
$$

where n is the turn ratio of the transformer. The turn ratio of primary and secondary side in 1 : n. As shown in (4), the effective voltage transferring to the secondary side is constant because the non-constant components are cancelled out due to the balanced input voltage.

Fig. 2 presents the synthesized output voltages of (3) and (4) at a certain switching period. Their magnitudes of the output voltages are determined by each DC-link voltage, and the duties are set by PWM to match the reference, (3). The summed voltage, v_{syn}, forms a staircase wave, but its average value is constant over a switching period.

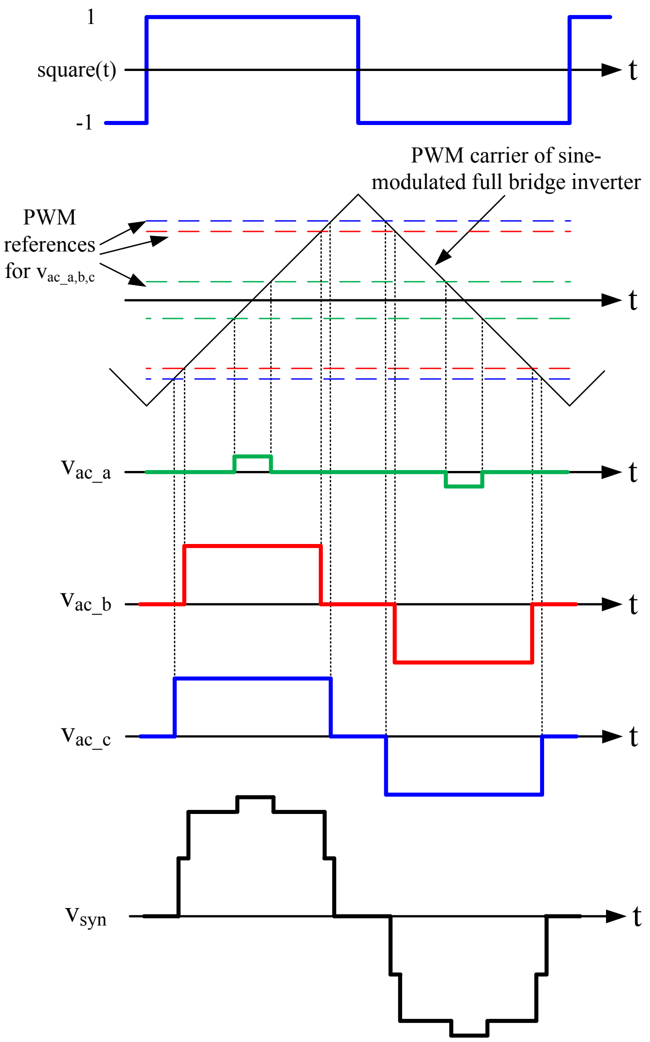


Fig. 2. Output voltage of the sine-modulated full-bridge inverter

When the output-side DC-link voltage of the high-frequency bidirectional rectifier is constant, the power transferring through the high-frequency multi-winding transformer can be achieved in similar manner of the PWM DC-DC converters [5]. It can be explained with an equivalent circuit, shown on Fig. 3. It includes three-phase sine-modulated full bridge inverters, three high-frequency transformers, with one secondary winding and one high-frequency bidirectional rectifier. This equivalent circuit is modeled in the point of view from secondary side of the transformer. In the circuit, v_{syn} is the sum of the output voltages of the sine-modulated full bridge inverter, including transformer turn ratio. And v_{rec} is the output voltage of the high-frequency bidirectional rectifier. It forms of bipolar square wave phase shifted from the function '*square(t)*' of the sine-modulated full bridge inverter. X means the sum of leakage inductance of the transformers. The approximate power transferring via the transformer in the switching frequency can be given as following.

$$
P = \frac{V_{s1}V_{r1}}{2X}\sin\phi, \tag{5}
$$

where V_{s1} and V_{r1} is the fundamental frequency component of the v_{syn} and v_{rec}, respectively. ϕ is the phase shifted angle between them. In the proposed scheme, V_{s1} and V_{r1} is set by the voltage level of DC-links, and the transferring power is controlled by adjusting the phase shift angle ϕ. Then, the

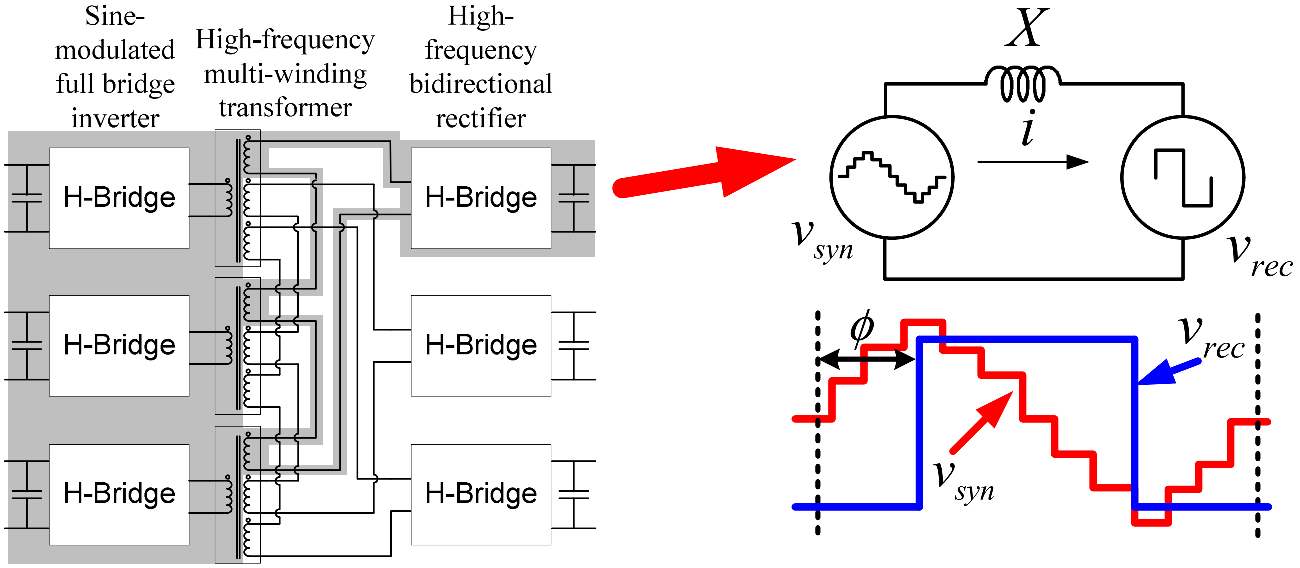


Fig. 3. Simplified equivalent circuit of the high-frequency power transfer part

output-side DC-link voltage can be controlled by transferring power control.

The output full bridge inverters share the DC-link with the high-frequency bidirectional rectifiers and they synthesize each single phase AC output. If the AC load is balanced, the output phase voltage synthesized by the inverters and current to each output full bridge inverter can be defined as followings,

$$v_{out\_a} = V_o \sin\left(\omega_o t\right),$$

$$v_{out\_b} = V_o \sin\left(\omega_o t - \frac{2}{3}\pi\right), \tag{6}$$

$$v_{out\_c} = V_o \sin\left(\omega_o t + \frac{2}{3}\pi\right),$$

$$i_{out\_a} = I_o \sin\left(\omega_o t - \psi\right),$$

$$i_{out\_b} = I_o \sin\left(\omega_o t - \frac{2}{3}\pi - \psi\right), \tag{7}$$

$$i_{out\_c} = I_o \sin\left(\omega_o t + \frac{2}{3}\pi - \psi\right),$$

where V_o and I_o is the magnitude of the output voltage and current, and ψ is the phase difference between output voltage and current. Then, considering the power balance, the output-side DC-link currents are derived as followings,

$$i_{dc\_out\_a} = \frac{V_o I_o}{2V_{dco}}\left[\cos(\psi) - \cos(2\omega_o t + \psi)\right],$$

$$i_{dc\_out\_b} = \frac{V_o I_o}{2V_{dco}}\left[\cos(\psi) - \cos(2\omega_o t - \frac{2}{3}\pi + \psi)\right], \tag{8}$$

$$i_{dc\_out\_c} = \frac{V_o I_o}{2V_{dco}}\left[\cos(\psi) - \cos(2\omega_o t + \frac{2}{3}\pi + \psi)\right],$$

where V_{dco} is the output-side DC-link voltages. These currents flow into the secondary side of the transformer. They have fluctuating component with twice of output frequency because of single phase AC output. However, this fluctuating current is not transferred to the primary side of the high frequency transformer. Because each phase of the winding is coiled on the secondary side of one transformer, the fluctuating components of the current are cancelled out and only average component are added and transferred to the primary side. Therefore, current flowing into the sine-modulated full bridge inverters can be simplified to a form of pure square wave, as following,

$$i_{ac} = I_{dc} square(t), \tag{9}$$

where I_{dc} is constant.

Considering the modulation of the sine-modulated full bridge inverters in (3) and the instantaneous power balance, the DC-link current flowing into the low-frequency bidirectional rectifiers can be derived as following equations.

$$i_{dc\_a} = I_{dc} mV \sin\left(\omega t - \varphi\right) sign\left(\sin\left(\omega t\right)\right),$$

$$i_{dc\_b} = I_{dc} mV \sin\left(\omega t - \frac{2}{3}\pi - \varphi\right) sign\left(\sin\left(\omega t - \frac{2}{3}\pi\right)\right),$$

$$i_{dc\_c} = I_{dc} mV \sin\left(\omega t + \frac{2}{3}\pi - \varphi\right) sign\left(\sin\left(\omega t + \frac{2}{3}\pi\right)\right). \quad (10)$$

Then, by the operation of the low-frequency bidirectional rectifier, the waveform of AC input phase current to the grid would be the sinusoidal one with desired phase angle, φ, like as (11).

$$i_{phase\_a} = I\sin\left(\omega t - \varphi\right),$$
$$i_{phase\_b} = I\sin\left(\omega t - \frac{2}{3}\pi - \varphi\right), \quad (11)$$
$$i_{phase\_c} = I\sin\left(\omega t + \frac{2}{3}\pi - \varphi\right), \text{ where } I = I_{dc} mV.$$

Fig. 4 shows the simplified single phase equivalent circuit of the proposed converter to explain the role of the input filter. In Fig. 4, E_s and L_s is the phase voltage and line inductance of the grid. R_f, L_f and C_f is the input filter inductor, damping resistor and capacitor, respectively. C_{dc} is the input-side DC-link capacitance. The converters after the low frequency bidirectional rectifier is modeled as a current source, i_s.

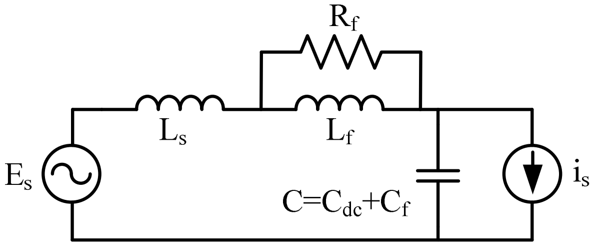


Fig. 4. Simplified single phase equivalent circuit of the proposed converter

The input filter has two functions. One is to suppress transferring switching harmonics into the grid. For that, the cut off frequency of the filter should be low enough. Besides, it should not be influenced by the line frequency. The cut off frequency is set properly considering these conditions. And to set the cut off frequency accurate, the L_f should be several times of Ls. The other function is to help distributing the voltage evenly, phase to phase, and across the stages. If there is a transient unbalance on the load, from the point of view of the grid, the voltage applied to the filter capacitor become different. Then, the unbalance condition would deteriorate. The larger filter capacitor helps reducing the problem. Also, when the converter is connected in series, the voltages applied to the filter capacitors across the stages, in same phase, can be different. The larger filter capacitor help balance the voltage across the stages. The filter parameters, L_f and C_f are chosen considering these issues.

IV. SIMULATION RESULTS

A simulation is performed to verify the feasibility of the proposed scheme. Set parameters are demonstrated on table 1.

TABLE I. PARAMETERS OF THE SIMULATION

Quantity	Value
Grid voltage	220V, 60Hz
Load/source voltage	220V, 50Hz
Input filter parameters	L_F ; 100µH C_F ; 100µF R_F ; 1Ω
Input-side DC-link capacitor	11µF
Output-side DC-link capacitor	500µF
Switching frequency of sine-modulated full bridge inverter and output full bridge inverter	10kHz

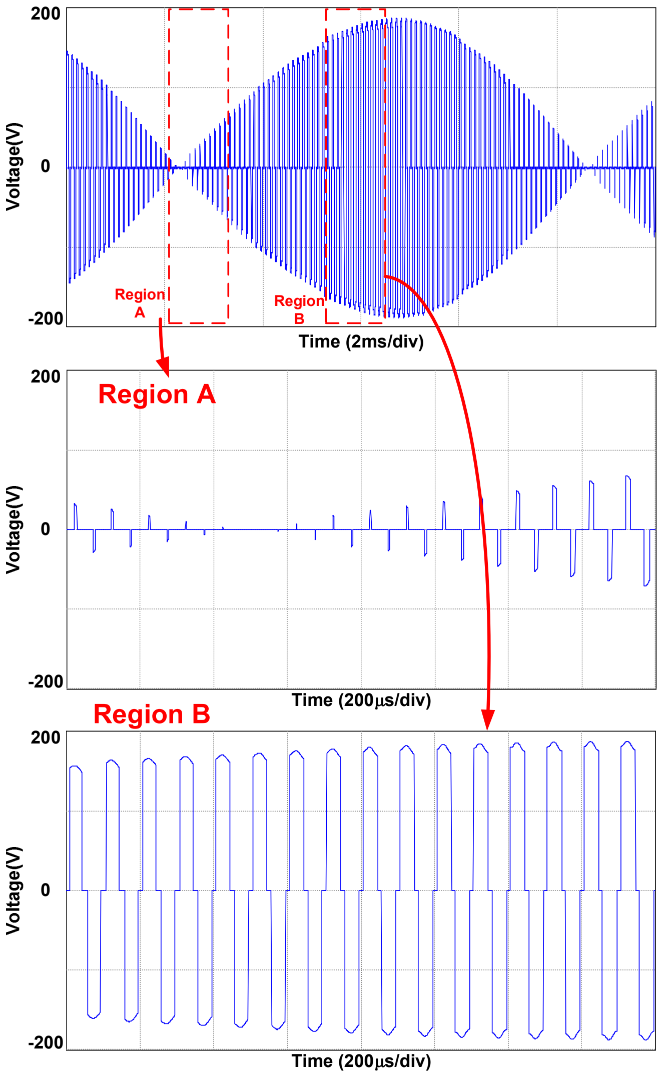
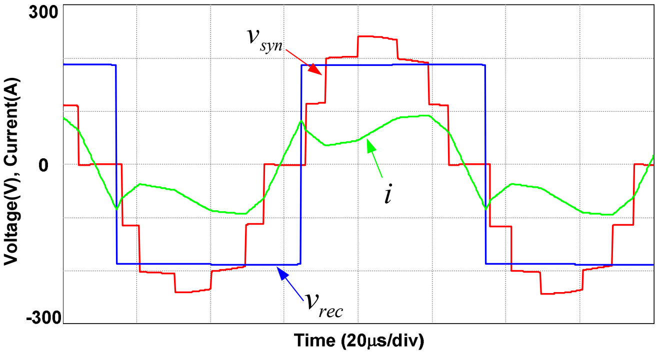


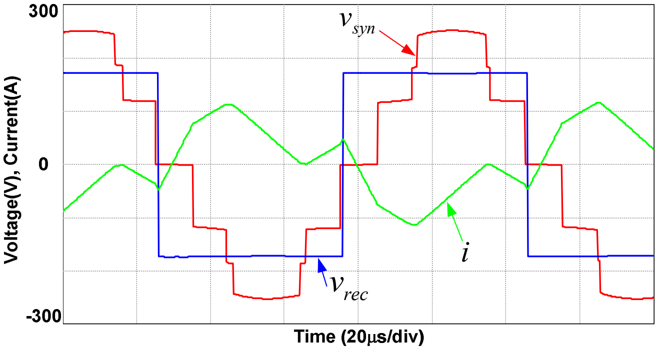
Fig. 5. Simulation waveform of output voltage of the sine-modulated full bridge inverter

One stage of the SUL converter links between 220V, 60Hz three-phase grid and other three-phase, 50Hz system. Both powering and regenerating simulation is performed. The output-side DC-link voltage is controlled to 180V, the same level of input-side DC-link.

Fig. 5 shows the output voltage of a sine-modulated full bridge inverter applied to the primary side of the transformers, which is presented in (3). According to (3), the pulse width is supposed to be increased as the magnitude of the dc-link voltage is high. The magnified waveforms in Fig. 5 show this tendency clearly.



(a) Powering operation

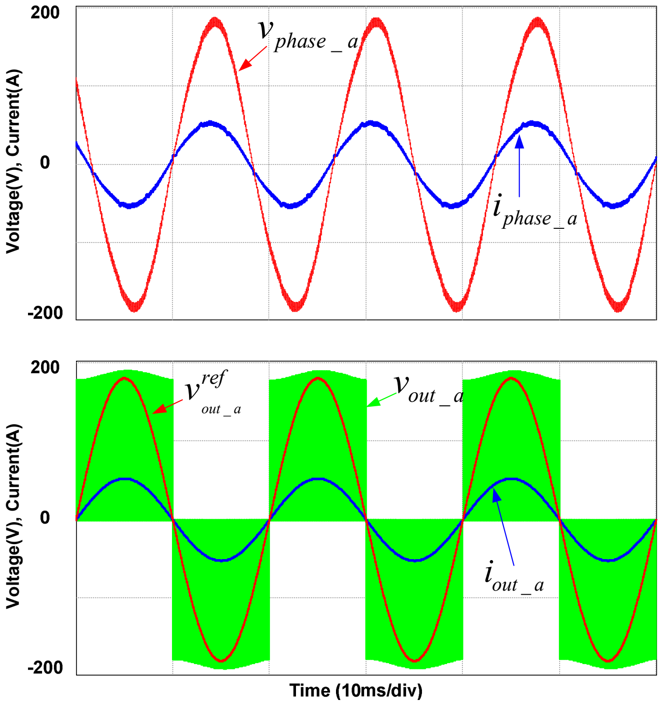


(b) Regenerating operation

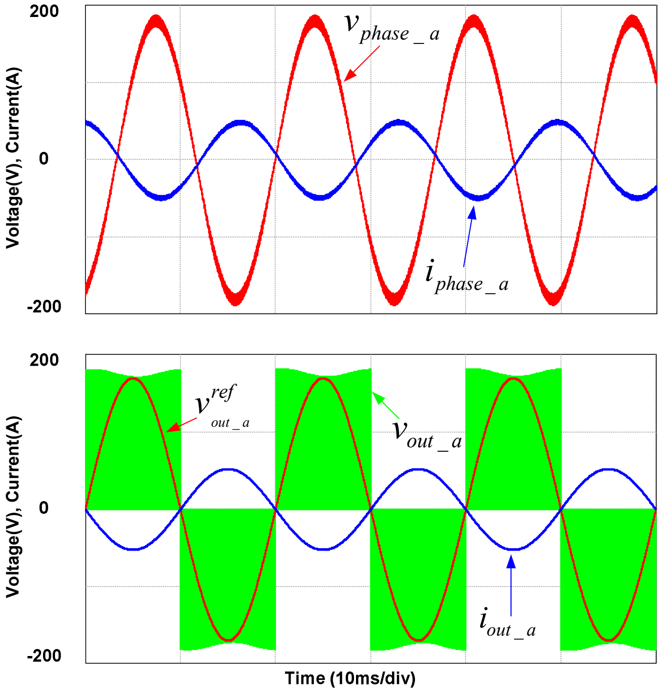
Fig. 6. Simulation waveform of voltage and current applied on the transformer

Fig. 6 shows the voltages applied on the high-frequency multi-winding transformer and the current flowing through it. Both powering and regenerating operation results are displayed. This figure supports the power transfer concept shown on Fig. 3. The phase shift angle between the voltages applied on primary and secondary side of the transformer, v_{syn} and v_{rec} determines the current flowing through the transformer and the power transfer.

Fig. 7 shows the phase voltage and current of the grid and output voltage and current of a load or a source at powering/regenerating situations. In both case, the amount of flowing power is 20kW. The input phase current has sinusoidal form and the magnitude and phase angle is determined by load condition. The result demonstrates a feasibility of the converter for interfacing different frequencies AC systems with bidirectional power flow capability.



(a) Powering operation



(b) Regenerating operation

Fig. 7. Simulation waveform of voltage and current applied on the transformer

V. EXPANDABILITY OF THE CONVERTER

The SUL converter has scalability due to its modular structure. It can be adopted for high voltage application by staking stages. Fig. 8 illustrates an example of the series con-

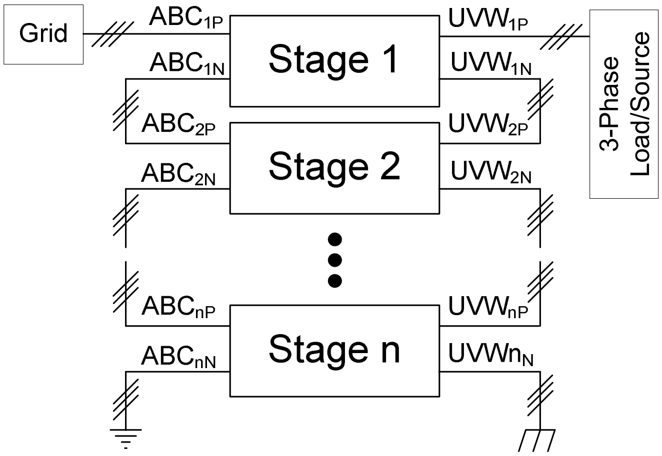


Fig. 8. Series connected structure of SUL converter

nection. Terminologies in Fig. 8 are quoted from Fig. 1.

Also, the output port can be extended by changing the winding arrangement of the transformers and adding the H-bridges. For example, in order to link two separate three-phase systems and grid, each transformer should have six secondary windings. Each winding is connected to the H-bridges. They compose two separate three-phase output-side, which can be connected to three-phase load or an energy source, individually. The DC-link voltages at the H-bridges of each output-side can be set separately by modifying the turn ratio. In addition, DC loads or sources can be attached in same manner. Fig. 9 shows an example. On its output-side, a three-phase load and a DC load is attached. The transformer has four isolated secondary windings and every single phase of H-bridge is connected to separate secondary winding of the transformer.

VI. CONCLUSION

This paper proposes the Series-connected Universal Link converter (SUL converter) as a power converter. The SUL converter can has multi outputs supporting bidirectional power flow. Both AC and DC loads and/or energy sources, such as a wind generator and fuel cells can be linked together. The proposed converter is suitable for grid connection because its input currents shape is a sinusoidal one, and this is realized without a PWM boost converter. Also, the power factor can be adjusted. The converter utilizes the high-frequency transformer as the galvanic isolation for grid safety instead of line-frequency transformer. These properties contribute to reduce the size of the converter. The converter consists of H-bridge modules. Therefore the converter can be directly connected to medium/high voltage grid by stacking the input-side H-bridges. Also, by simple rearranging of transformer and H-bridges, output ports can be modified. With this characteristic, the SUL converter could be used as a building block for universal grid connection applications.

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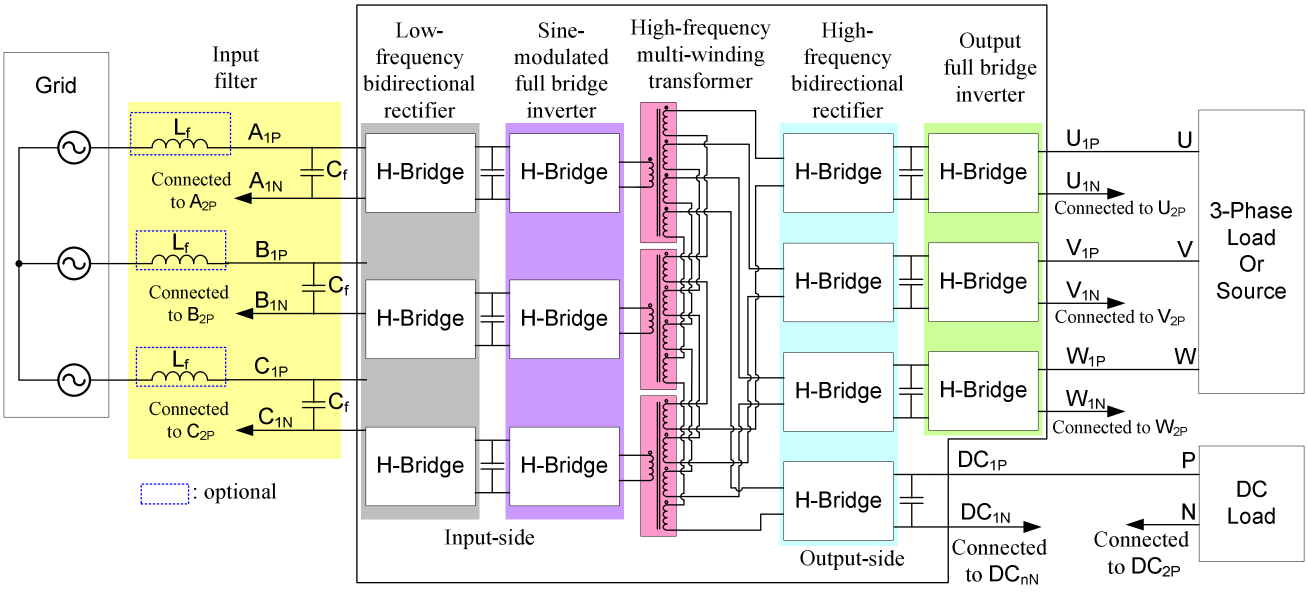

Fig. 9. An example of extended structure of SUL converter for a three phase load and DC load

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