Single-Phase Single-Stage Power-Factor-Corrected Converter Topologies

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***Abstract*—Single-phase single-stage power-factor-corrected converter topologies are reviewed in this paper. The topologies discussed in the paper are related to ac–dc and ac–ac converters that are classified on the basis of the frequency of the input ac source, the presence of a dc-link capacitor, and the type of control used (resonant or pulsewidth modulation). The general operating principles and strengths and weaknesses of the converters, which the authors have investigated over the last decade, are discussed in detail, and their suitability in practical applications is stated. Considering practical design constraints, it is possible to effectively employ many single-stage converter topologies in a wide range of applications.**

***Index Terms*—AC–AC converters, ac–dc converters, harmonic reduction, power-factor correction (PFC), power quality, single-stage converters, switch-mode power supplies.**

I. Introduction

It is generally the task of power electronics to convert the electric power available from a power source into the form best suited for user loads. Some sort of power converter is required to serve as an interface between power source and load to achieve this objective. The input power source for equipment handling less than 3 kW of power is usually a single-phase ac source. The converter itself may be an ac–dc or an ac–ac converter, with or without transformer isolation, depending on the requirements of the load.

It was very common in the past to use a simple, single-phase diode bridge rectifier with a capacitive output filter as the first stage of the converter as is shown in Fig. 1. The diode bridge rectifies the ac input voltage and the capacitor smoothes out the resulting voltage to make it an almost pure dc waveform. The current drawn from the ac utility source, however, is very nonsinusoidal because the bridge diodes conduct current only when the rectified input voltage is equal to or greater than the dc capacitor voltage. It is only then that current flows to charge the capacitor.

For any electrical equipment drawing power from the utility, the input power factor is an indication how effectively this is accomplished. The diode bridge rectifier shown in Fig. 1 has a poor power factor because of the nonsinusoidal current it draws from the utility. This current has a very high peak and contains large harmonic components that are injected into the utility supply. If vast numbers of such converters were to be used in industry, the harmonics that would be injected in the utility would be so large that they would create a need for increased volt-ampere ratings of utility equipment (i.e., transformers, transmission lines, and generators) and distort the utility voltage. Since a severely distorted ac utility voltage can damage sensitive electrical equipment, regulatory agencies around the world have established standards on the current harmonic content produced by electrical equipment, such as EN61000-3-2 [1]. The significant rise in the use of electrical equipment in recent years due to increased consumer demand has made the inefficient use of power less tolerable than in the past.

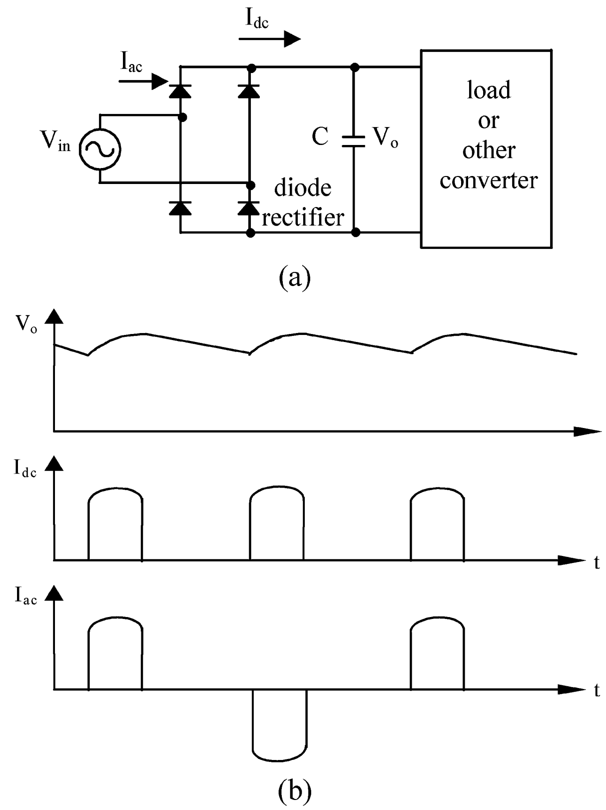

Fig. 1. (a) Single-phase diode bridge rectifier with capacitive output filter. (b) Diode bridge rectifier output voltage, output current, and input current waveforms.

Stricter regulatory agency standards on harmonic content have led to the demise in popularity of the simple diode-bridge rectifier as the front-end converter in electrical equipment operating off of an ac supply. More and more, electrical equipment manufacturers are being forced to improve or "correct" the input power factor of products supplied by an ac utility source.

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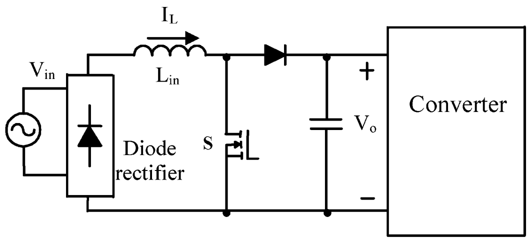

Fig. 2. AC–DC PWM boost converter.

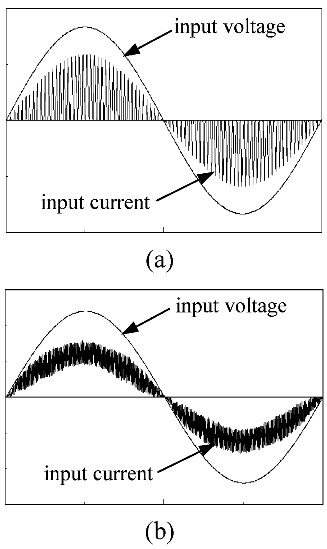

Fig. 3. AC–DC boost PFC converter input current waveforms. (a) Discontinuous current. (b) Continuous current.

The most common approach to power factor correction (PFC) in a front-end ac–dc converter is to use an active, pulsewidth-modulated (PWM) ac–dc boost converter, which is shown in Fig. 2 along with some typical input current waveforms in Fig. 3. The converter can produce input current waveforms that are either continuous and sinusoidal with some ripple, or discontinuous and bounded by a sinusoidal envelope with substantially more ripple. The current in both cases is effectively sinusoidal.

Although an excellent input power factor can be achieved by using an ac–dc PWM boost converter as the front-end converter in an overall two-stage ac–dc or ac–ac converter, the overall converter becomes more expensive and complicated than it would be if a diode-bride rectifier were used instead. This is because there are two separate switching converter stages present, each requiring a separate controller. In order to reduce the cost and complexity of the overall converter, yet operate with a power factor better than that produced by a converter with a front-end ac–dc diode-bridge rectifier, power electronics researchers have proposed converters that combine the PFC and power conversion functions in a single converter.

Single-stage power conversion is a topic that has been of substantial interest to power electronics researchers in recent years, and numerous converters have been proposed. These converters can generally be classified according to the diagram shown in Fig. 4. In this paper, a number of single-stage converters will be reviewed according to this classification. The issues associated for each converter type will be discussed and various approaches for PFC will be examined. The focus of the paper will be placed on single-stage converters that the authors have investigated over the past decade. The key points of the paper will be summarized at the end.

II. Converters Operating With a Low-Frequency AC Source and Without a DC-Link Capacitor

An ac source can produce an ac voltage with low frequency such as the standard 50/60-Hz utility voltage frequency, or an ac voltage with high frequency such as 100 kHz. In both cases, the most efficient utilization of power will occur when the current flowing out of the source is sinusoidal and in phase with the source voltage. Given the nature of the two types of sources, however, techniques that are appropriate for one type of source are not appropriate for the other.

According to the classification diagram shown in Fig. 4, single-stage converters operating with a low frequency ac source can be further divided into two types—converters with very small or no dc-link capacitor and converters with a large dc-link capacitor. Converters of the first type generally have the output of a front-end diode bridge rectifier fed directly into the input of a converter, but the diode rectifier does not have a large capacitive output filter. Since this capacitor does not exist, current can flow from the input source to the converter throughout the line cycle instead of being restricted to flowing only during the limited portion of the cycle when the input voltage is greater than the capacitor voltage, as is the case with the converter shown in Fig. 1. Without a large capacitor placed at the diode bridge output, the single converter can be made to operate in a way that shapes the input current so that an excellent input power factor can be achieved. Moreover, the absence of a large dc-link capacitor also reduces the size and weight of the converter.

In this section of the paper, three types of single-stage converters without a dc-link capacitor are examined—resonant ac–dc converters, PWM ac–dc converters, and ac–ac converters that produce a low-frequency ac waveform. For each converter type, the key issues concerning converter operation are discussed and example converters are presented.

A. AC–DC Converters

1) Resonant Converters: A converter must draw a sinusoidal current from the source that is in phase with the input ac voltage if it is to be operated with unity input power factor. The converter must therefore be heavily loaded near the peak of the input line and lightly loaded near the zero. Parallel and series-parallel resonant converters, such as the one proposed in [2] and shown in Fig. 5, can operate with high input power factor and constant output voltage because they can be made to have a high voltage gain under light-load conditions and a lower gain at full load. The voltage gain depends on the ratio between the switching frequency and the resonant frequency. It was demonstrated in [2] that it is possible to make a resonant converter operate with unity input power factor by adjusting the switching frequency along the input line cycle. Moreover,

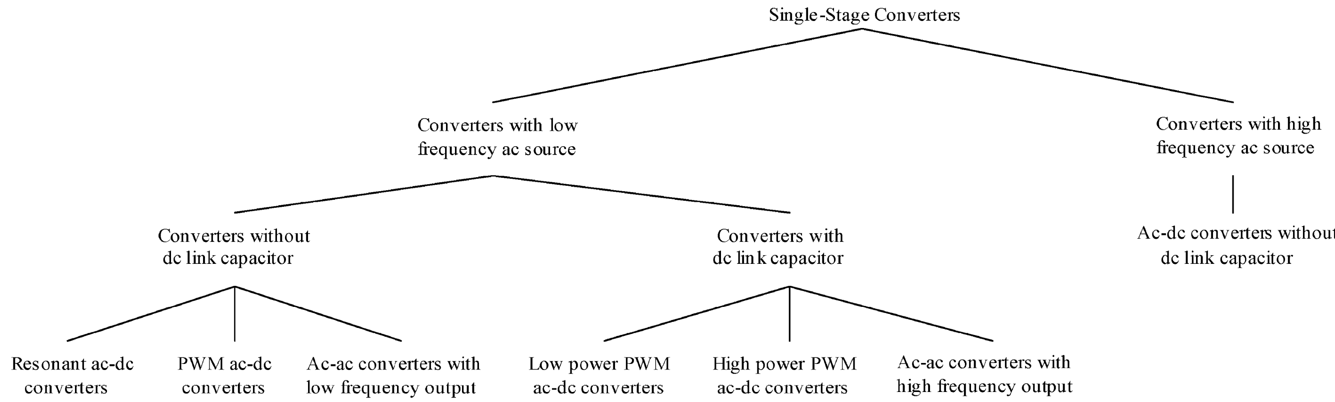

Fig. 4. Classification of single-stage converters.

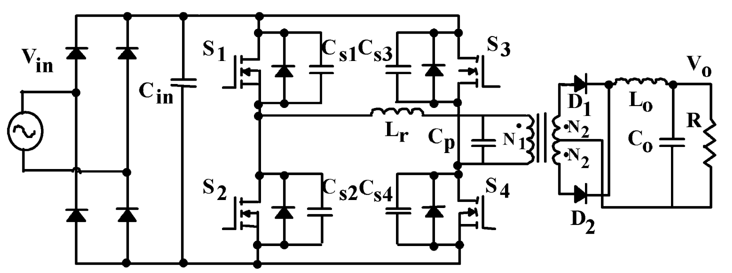

Fig. 5. Single-stage ac–dc parallel-resonant converter.

parallel and series-parallel resonant converters can operate with zero-voltage switching (ZVS) if they are made to operate with a switching frequency that is above the resonant frequency. This allows the transformer primary current to lag the primary voltage so that when a converter switch is turned off the current that was flowing through that switch is forced to flow through the body diode of the other switch in the same leg so that the switch can be turned on with ZVS. It should be noted that the dc-link capacitor shown in Fig. 5 is a small capacitor intended to filter out high switching frequency noise.

The main disadvantage of operation of parallel and series-parallel ac–dc converters in the manner described above is that the total harmonic distortion (THD) of the input current is high (typically 30% at full load) if there is no active control of the input current. If such a control is used, then implementing an input current controller that can actively control and monitor converter current requires a current sensor and a multiplier that increases the complexity of the converter significantly. A relatively simple control technique for resonant converters that can ensure ZVS converter operation under all operating conditions and near-unity power factor was proposed in [3].

The power circuit and the control block diagram of a series-parallel resonant converter that can be implemented with this technique are shown in Fig. 6. A small low-pass filter $(L_{\rm in}, C_{\rm in})$ on the dc bus is used to attenuate the high-frequency harmonics generated by the inverter. The inverter produces a high-frequency ac waveform v_{ab} that is applied to the resonant circuit formed by C_s, L_s, and C_p. When operating above the resonant frequency, the transformer primary current i_s lags the voltage v_{ab}. As a result, the current has the polarity required to reset the snubber capacitors and provide operation with ZVS. At the output side, a diode rectifier converts the high-frequency

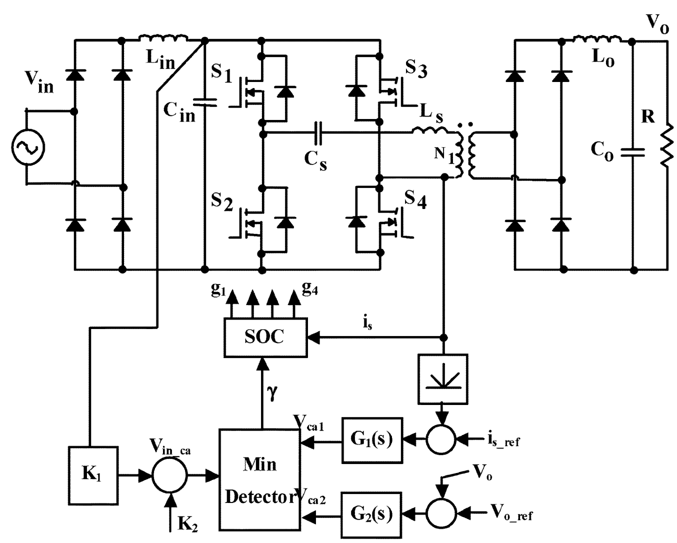

Fig. 6. Single-stage ac–dc series-parallel resonant converter.

ac waveform across the parallel resonant capacitor into a unidirectional voltage. The output filter formed by L_o and C_o attenuates both the high-frequency ripple generated by the output rectifier and the low-frequency ripple resulting from the pulsating nature of the power absorbed by the converter from the input ac line.

The control circuit is comprised of a self-sustained oscillation circuit (SOC), a current limiter, and an output voltage controller. In addition, the control circuit uses the input dc-link voltage to reduce the THD of the input current. The SOC, which is described in detail in [3], generates the gating signals for the inverter and ensures its operation with ZVS. The input of the SOC,

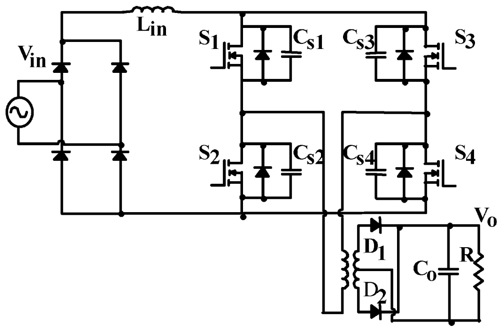

Fig. 7. Basic single-stage ac–dc PWM full-bridge converter without large dc-link capacitor.

a control angle γ, is defined by the following three parameters, which are: 1) the output voltage v_{ca2} of the controller $G_2(\mathrm{s})$, which is used to regulate the output voltage v_o during normal operation; 2) the output voltage v_{ca1} of the resonant current controller $G_1(\mathrm{s})$, which is used to limit i_s during short circuit, overload, and the startup operation; and 3) the voltage v_{mca}, which is used to improve the input power factor and reduced the THD of the input current I_{in}. As a result, the proposed scheme allows the converter to operate with a constant output voltage, a limited resonant circuit current, and a low input current THD.

Experimental results obtained from a 220-Vrms input, 100-Vdc output, 500-W prototype operating with a minimum switching frequency of 100 kHz were presented in [3]. It was shown the converter can operate with near-unity power factor and a maximum efficiency of about 91% at full load for loads ranging from about 15% to full load.

The output of these converters has a large low-frequency current ripple and requires large filters because there is no or very little capacitor in the dc link. These types of converters are suitable for online ac UPS systems because the low-frequency ripple from the dc output need not be removed as this voltage is converted to low-frequency ac as the output of the UPS.

2) PWM Converters: Although single-stage resonant converters can operate with ZVS, they have high voltage and/or current switch stresses and need to operate with variable switching frequency control. The latter complicates the design of converter magnetics and filters, limits the converter operating range, and complicates the synchronization of the operation of one converter with other converters. Resonant converters are therefore suitable to a limited number of applications, and converters operating with PWM control and a fixed switching frequency are preferable.

The basic ac–dc single-stage PWM full-bridge converter with a large dc-link capacitor is shown in Fig. 7. Other converters of this type are variations of this converter with extra circuitry added to improve performance. The converter operates as follows. If a pair of diagonally opposed switches (S_1 and S_4 or S_2 and S_3) is on, then the current flowing through the input inductor L_{in} will fall as energy is transferred from the primary side of the converter to the output. If the dc bus is shorted, either by turning on all the converter switches or at least two switches in the same converter leg at the same time, then the input inductor current rises as the full input voltage is placed across L_{in} and no energy transfer to the load takes place.

The operation of this converter can be considered to be analogous to that of the conventional, single switch, ac–dc PWM boost converter because both converter have the same two key modes of operation—one mode where the dc bus is shorted, another mode where the dc bus is not shorted and energy from the input is transferred to the load. The input current can be made to be fully discontinuous, bounded by a sinusoidal envelope, or it can be made to be fully continuous and almost purely sinusoidal just like the input current of a PWM boost converter. Moreover, very similar soft-switching techniques can be used to help the converter switches operate with ZVS, with similar improvements in efficiency.

The use of soft-switching in a single-stage PWM full-bridge converter with a large dc-link capacitor was examined in [4], in the converter shown in Fig. 8. This converter has an auxiliary circuit placed across its dc link to help the full-bridge converter switches operate with ZVS. The auxiliary circuit is activated before any converter switches are turned on to short the dc bus, and current is made to flow through the body-diodes of all four switches so that the switches can be turned on with ZVS.

Although ac–dc single-stage PWM full-bridge converters that do not have a large dc-link capacitor can operate with near-unity input power factor, they have a serious drawback that limits their use. This is the fact that voltage overshoots and ringing on the dc-link voltage can be caused by the interaction of the leakage inductance of the isolation transformer and the full-bridge switch output capacitances. The overshoots and ringing can be extremely severe, especially whenever two switches are turned off. Some sort of voltage clamp must be placed across the dc bus on the primary side to reduce them. The clamp can be a simple resistor–capacitor–diode (RCD) clamp, or a sophisticated nondissipative clamp. Issues associated with voltage overshoots and ringing generally limit the maximum power of ac–dc single-stage PWM full-bridge converters that do not have a large dc-link capacitor to about 1–2 kW.

As with the resonant converters discussed in Section II-A.1, the output of these converters carries a large low-frequency current ripple and requires large filters. They are, therefore, suitable for online ac UPS systems or in some batteryless offline telecommunication systems to convert ac input voltage to -48 V dc output voltage for downstream converters.

B. AC–AC Converters With Low-Frequency Output

Single-phase ac–ac power converters are used to power optical fiber/coax cable hybrid networks and are required to produce a special, low-frequency trapezoidal-shaped waveform. These converters are typically two-stage converters with an ac–dc PWM boost converter for PFC and a dc-ac inverter. It is possible, however, to achieve near-unity input power factor in ac–ac converters for optical fiber/coax cable hybrid networks using only a single converter stage. One of the first methods for accomplishing this was proposed in [5] and is shown in Fig. 9. In Fig. 9, an *RL* branch is connected in series with the input source to represent the source impedance, and a second-order *LC* filter is used at the inverter output to filter out high-frequency harmonics. A small capacitor is placed in the dc link simply to filter out high-frequency noise.

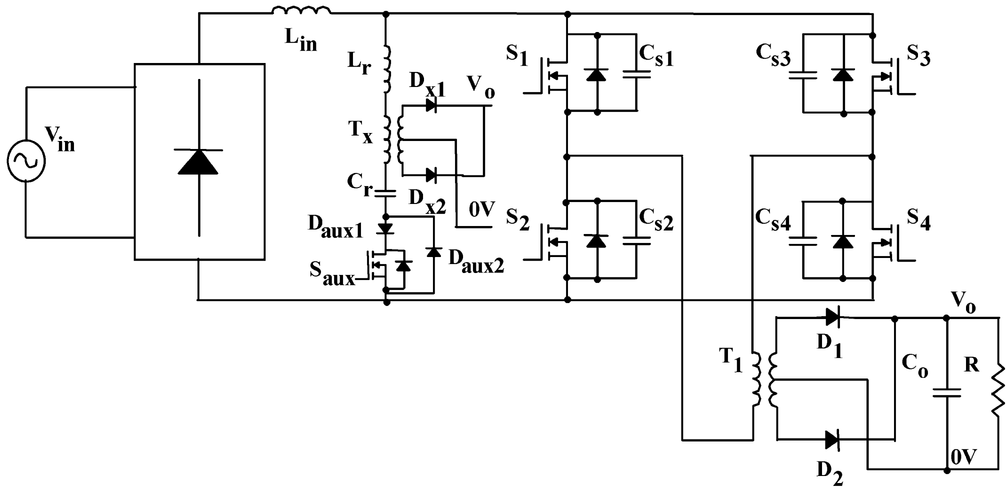

Fig. 8. ZVS current single-stage ac–dc PWM full-bridge converter without large dc-link capacitor.

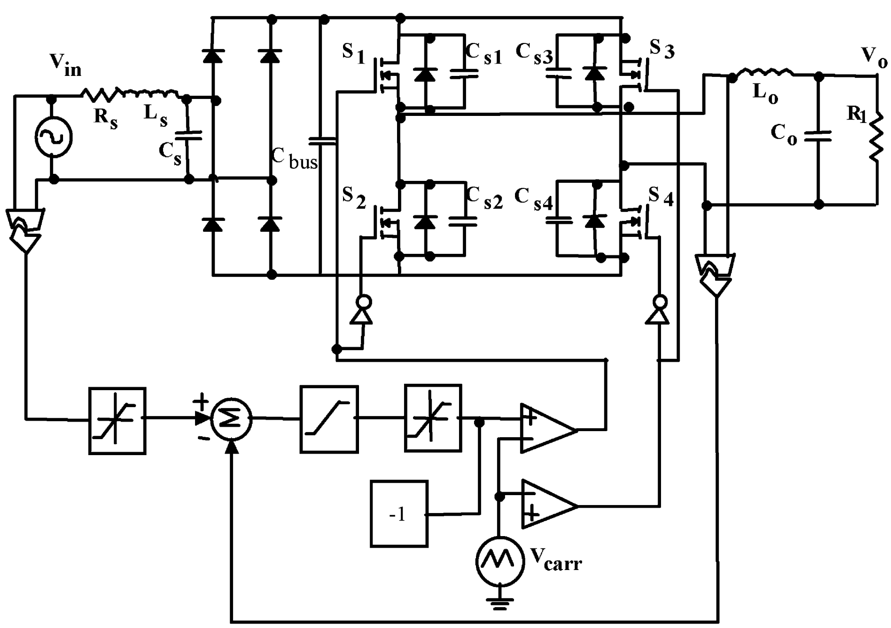

Fig. 9. A near-unity power factor single-phase trapezoidal ac power supply with minimum dc-bus capacitor: Triangular carrier-based output voltage integral PWM control.

The control technique shown in Fig. 9 is a voltage integral control technique that integrates the volt-seconds of an error waveform that is the difference between the inverter output and a reference waveform. A trapezoidal-shaped reference is generated by passing a sinusoidal voltage that is in phase with the ac mains through a limiter. The integrated error waveform is a modulating waveform that is then compared to a triangular carrier waveform to generate the appropriate PWM gating signals for the four inverter switches. The ac output is synchronized with the dc ripple so that the zero-crossing of the inverter output ac trapezoidal voltage waveform corresponds to the lowest point of the dc bus. This is done to better utilize the dc-bus voltage and to avoid the adverse effect of the dc voltage fluctuation caused by the presence of a small capacitor at the dc bus.

The main advantage of this control technique is that the control loop has a fast response because it measures the voltage right after the inverter instead of from the load. The loop can also be easily designed based on the slope constraints of the modulation wave versus the carrier waveform. An improvement to the control technique was proposed in [6] and is shown in Fig. 10. The technique is a reset integral control technique (also known as one-cycle control) that forces the average value of the switch variable to follow the reference within one cycle. The technique rejects power source perturbations and corrects switching delays if the dc-bus voltage is measured at the inverter output.

In [6], the performance of the reset integral control technique was experimentally compared to that of the voltage integral control technique and a variable-switching frequency, hysteresis based control technique. The comparison of the three techniques was made on a 120-Vrms/60-Hz input, 90-Vrms/60-Hz 2-A trapezoidal output, 40-kHz switching frequency power supply that had a 10-μF dc-bus capacitor. It was found that the input power factor at rated load for all three techniques is greater than 0.9, that the power factor decreases as load

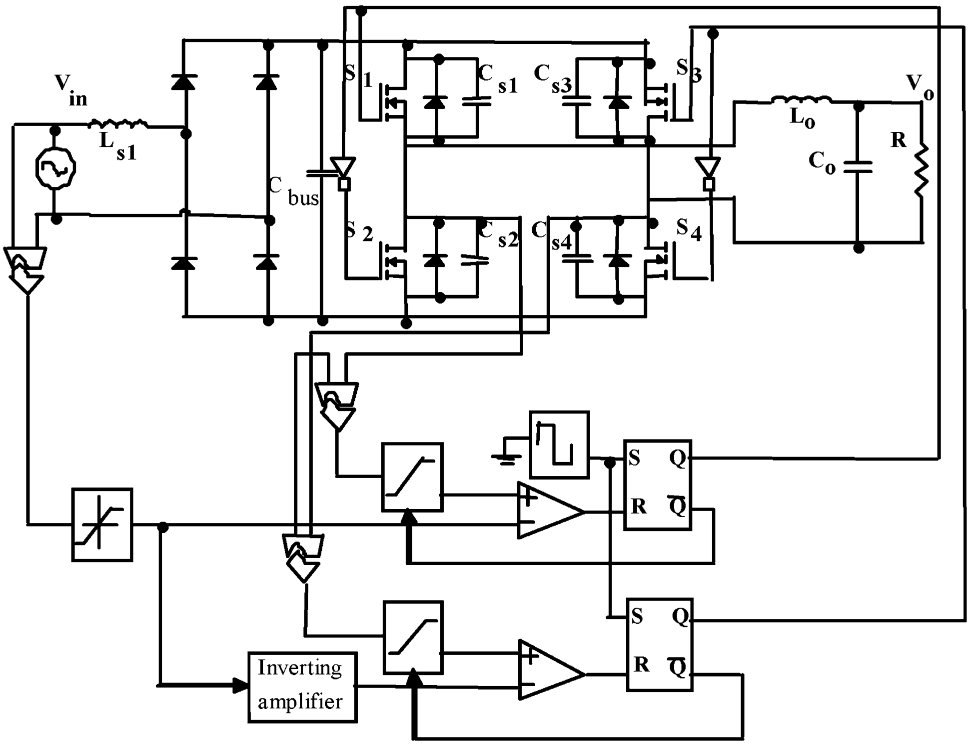

Fig. 10. A near-unity power factor single-phase trapezoidal ac power supply with minimum dc-bus capacitor. One-cycle reset integral PWM control.

decreases, and that there are small differences in power factor with different techniques, but that the reset integral control gives the best overall performance. Since all three techniques were implemented on an ac–ac converter that consisted of a single switching converter, the converter efficiency remained high in all three cases, above 90% for loads above 50%.

It was determined in [6], however, that the most important factor in the operation of an ac–ac converter for hybrid networks is the dc-bus capacitor. The influence of its value on power factor and input current THD was examined and it was shown that the power factor decreases as the capacitance increases (down to 0.6 for $C = 400\ \mu$F) with the THD increasing accordingly. The ability of the converter to operate with a very fast response was confirmed in [7], where it was used as part of a UPS system. Experimental results confirming the UPS system's ability to smoothly make the transition from supply to battery and vice versa under various transient conditions were presented in [7], and the reader is referred to this paper for further details.

III. Converters Operating With a Low-Frequency AC Source and With a DC-Link Capacitor

Single-stage converters that do not have a large bulk capacitor in their dc link are very attractive because they have very high input power factor. These converters, however, cannot be used in all applications because they have the following drawbacks.

1) The diode bridge output voltage is a rectified sinusoid, which is a dc voltage with a large low-frequency ac component. If the input source has a line frequency of 60 Hz, then this ac component has a 120-Hz frequency. In the case of ac–dc converters, this component will appear at the converter output unless it is filtered out using a large output filter. The need for such a filter is a drawback because of its size and weight and because it slows down the converter's ability to respond changes in line and load conditions. The existence of the large 120 Hz component at the output limits the use of single-stage converters with no dc-link capacitor to applications such as online UPS systems where this component is not an issue.
2) It is difficult to operate these converters with both ZVS and a fixed switched frequency. As was discussed in the previous section, resonant ac–dc converters can achieve ZVS operation, but must operate with a variable switching frequency and higher switch stresses. PWM ac–dc converters have voltage overshoots and ringing caused by the interaction of the transformer leakage inductance that need to be clamped either by simple, dissipative snubbers or by sophisticated nondissipative clamping circuits.

These drawbacks can be eliminated if a large capacitor is placed in the dc link of a single-stage converter, after the diode bridge output and before the converter itself. In this section of the paper, three types of single-stage converters with a dc-link capacitor are examined—low-power PWM ac–dc converters, PWM full-bridge ac–dc converters, and ac–ac converters that produce a high-frequency ac waveform. For each converter type, the key issues concerning converter operation are discussed and example converters are presented.

A. AC–DC Converters

1) Low-Power PWM AC–DC Converters: One of the very first single-stage converters with a dc-link capacitor was the forward converter proposed in [8] and shown in Fig. 11. It can be seen that the input inductor of this converter is connected to the forward converter switch. The input inductor current rises and

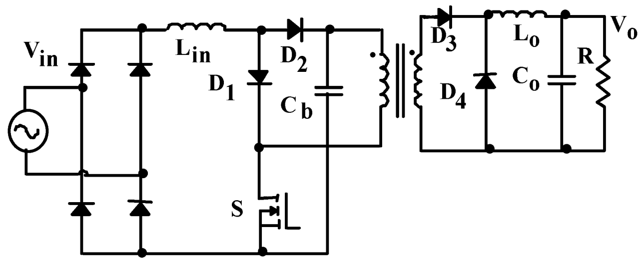

Fig. 11. Single-stage single-switch ac–dc forward converter with transformer winding proposed in [8] (demagnetizing winding not shown).

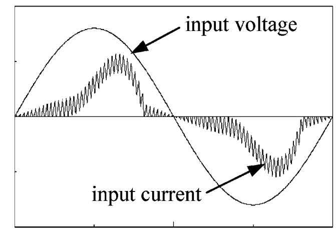

Fig. 12. Typical input voltage and current waveforms for a single-stage converter with input section operating in SCM.

energy transfer from dc-link capacitor C_b to the output takes place when the switch is on. This current falls and the output current freewheels through diode D_{o2} when the switch is off. By properly designing the input inductor so that the input current always discontinuous, the converter will operate with an input current waveform like the one shown in Fig. 3 while simultaneously regulating the output voltage with constant duty ratio.

A fundamental property of single-stage converters such as the one shown in Fig. 11 is that there is no control of the dc-link voltage because there is no separate converter that can control it as there is in a two-stage converter. This voltage is dependent on the energy equilibrium established between the energy flowing into the capacitor from the input inductor and the energy flowing out of the capacitor and transferred to the output. The net energy transferred in and out of the dc-link capacitor over a half line cycle must be zero if the converter is operating under steady-state conditions.

The absence of an independent controller to regulate the dc-bus voltage presents challenges to their design. There are several key criteria to consider when designing these converters to operate with a universal input voltage (90–265 Vrms). One of these is the primary-side dc-link voltage, which can be very high (i.e., >700 V) when the output load is very light. This voltage should be less than the commonly accepted limit of 450 V dc to minimize the voltage stresses of the converter switch and the size of the dc-link capacitor. Another is the input current, which must have a harmonic content that satisfies regulatory agency requirements. The task of improving input power factor is more difficult in ac–dc converters that have a large dc-link capacitor than it is in converters that do not have this capacitor. A third criterion is the output ripple current, which should be as small as possible to limit the amount of filter capacitance needed at the output. The amount of filtering needed at the output is much less than that for an ac–dc converter without a dc-link capacitor because there is no large, low-frequency (120 Hz) ac component but only high, switching frequency components.

A single-stage converter can operate in any one of several possible combinations of operating modes. The output section of the converter can operate in either the discontinuous conduction mode (DCM) or the continuous conduction mode (CCM). The input section can operate in the discontinuous conduction mode (DCM), the continuous conduction mode (CCM), or a semicontinuous conduction mode (SCM) that is a combination of DCM and CCM. An example of an SCM input current is shown in Fig. 12. Although an SCM waveform is nonsinusoidal, it is possible to design a single-stage converter to operate with an input SCM current waveform that can comply with standards set for electrical equipment by regulatory agencies.

There are advantages and disadvantages associated with each single-stage converter operating mode with respect to the three key design criteria of dc-bus voltage, input current, and output ripple. The converter can be made to operate with a fully continuous, sinusoidal input current waveform by tracking the input current and appropriately adjusting the converter duty cycle throughout the input line cycle. It is not, however, recommended that this be done because the converter in this case would have a considerable low-frequency component in its output current, like a converter without a dc-link capacitor. Single-stage ac–dc converters are, therefore, usually made to operate with a fixed duty ratio and with either DCM or SCM input current.

The following steady-state characteristics should be considered when designing a single-stage ac–dc converter.

1) Operating a converter with input DCM will result in an excellent power factor, but the dc-bus voltage may become very high. Operating a converter with input SCM will result in a lower dc-bus voltage and a lower power factor.
2) Operating a converter with output CCM may result in a very high dc-bus voltage. Operating a converter with output DCM will reduce the dc-bus voltage, but will increase current stresses in the converter devices, switch turn-off losses, and EMI noise.
3) The dc-bus voltage is independent of the load when both input and output converter sections operate in DCM, or when the output alone is in CCM. It is dependent on the load for any other combination of input and output operating modes.

A detailed explanation as to why these characteristics exist in ac–dc single-stage converters that have a large dc-link capacitor can be found in [9].

It was suggested in [8] that both the input and output section of the converter shown in Fig. 11 operate so that the current in each section is in DCM. Operating the converter with this combination of current conduction modes keeps the switch from having a high peak voltage stress at high input voltage and light load, while maintaining an excellent input power factor. A DCM output, however, is less acceptable when the output current is high because of the very high peak currents that would result. Since the purpose of operating the converter with a DCM output is to reduce the dc-bus voltage, power electronics researchers

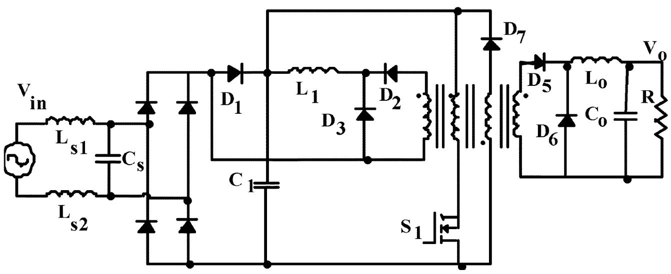

Fig. 13. Single-stage single-switch ac–dc forward converter with transformer winding proposed in [10].

have been motivated to find ways of doing this, yet operate with an output current with less ripple.

It is presently common to further reduce the switch voltage stress by using an auxiliary winding from the main converter transformer. One of the first converters in which this was done was proposed in [10] and is shown in Fig. 13. This converter works as follows. Power is transferred from the dc-bus capacitor to the secondary when switch S_1 is turned on. If the turns ratio between the primary and auxiliary windings is unity, then a voltage equal to approximately the full input voltage is applied across the input inductor, causing the inductor current to rise. When S_1 is turned off, power ceases to be delivered to the load, and the input inductor current forces diode D_3 and two of the input diode bridge rectifier diodes to conduct. A net negative voltage appears across the inductor, which reduces the current to zero. Since no power is delivered to the load, the inductor current charges the dc-bus capacitor.

This converter uses variable-switching-frequency control to further reduce the dc-bus capacitor voltage when the converter is operating with a high input voltage. Present-day single-stage converters, however, can now operate with fixed-frequency PWM control under all line and load conditions, and can operate with output CCM through a better use of the auxiliary transformer winding. It is possible to satisfy the key design criteria for low power converters, and techniques for doing so have been presented in numerous publications (i.e., [11]–[13]). In general, these converters can provide output voltages of 3.3–5 Vdc and about 100-W output power for a universal input voltage (90–265 Vrms).

2) High-Power PWM AC–DC Converters: Just as with lower power converters, higher power ac–dc single-stage full-bridge converters with a large dc-link capacitor have been proposed. One of the first converters of this type was proposed in [14] and is shown in Fig. 14. This converter is based on the converter proposed in [10] and shown in Fig. 13 and operates in a similar manner.

A voltage equal to the dc-link voltage, but with opposite polarity, is made to appear across the auxiliary transformer winding whenever diagonally opposed converter switches are on. This voltage cancels out the dc-bus voltage at the right-hand side of the inductor, making the net voltage across it zero, causing the input inductor current to rise. Whenever two top switches or two bottom switches are on, the voltage across the main transformer winding is zero, and so too is the voltage across the auxiliary winding. This results in a net negative voltage equal to the difference between the dc-bus voltage and

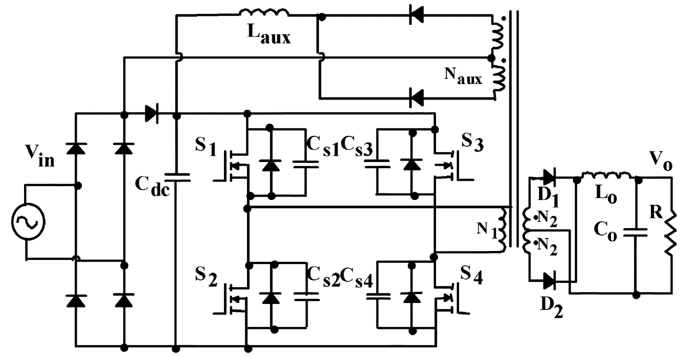

Fig. 14. Single-stage voltage-fed PWM converter proposed in [14].

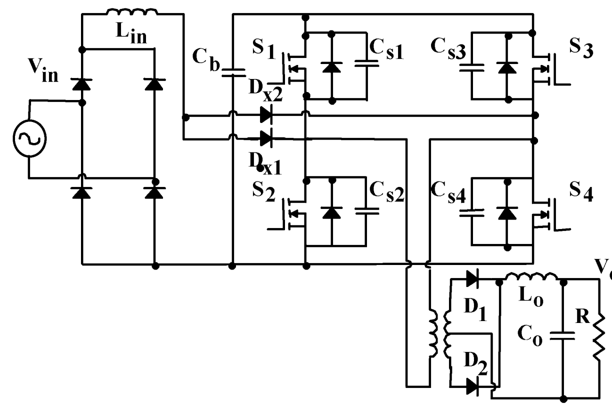

Fig. 15. Single-stage PWM full-bridge converter proposed in [15].

the input voltage appearing across the inductor, thus causing the input inductor current to fall. Energy transfer from the dc-bus capacitor to the load happens in the same way as it does in a standard PWM dc-dc full-bridge converter, and the converter can operate with the same phase-shift control technique used in a standard converter.

Single-stage PWM ac–dc converters share many of the same characteristics as the low power converters discussed in Section III-A.1—most notably, the primary-side dc-link voltage is not fixed at a particular level. It may vary considerably if line and/or load conditions are varied because it is dependent on the equilibrium between the energy pumped into C_b and that pumped out of it when the converter is operating at steady state. The main drawback of the converter shown in Fig. 14 is that the dc-bus voltage is very high and exceeds the desired 450-V limit when the input voltage is high. This is the case even though both input and output converter sections are operating in DCM.

An ac–dc single-stage PWM converter with a lower dc-link voltage was proposed in [15] and is shown in Fig. 15. The lower dc-link voltage was achieved as a result of the topology itself and the SCM operation of the input section of the converter. The converter is very similar to the conventional PWM full-bridge converter with a diode bridge rectifier, *L–C* filter front-end. The main difference is that the input inductor, L_{in}, is connected to both bottom converter switches through diodes. This allows the bottom switches to shape the input current while the converter is performing dc-dc conversion in a way similar to that of a standard full-bridge converter. The converter is in an energy-transfer mode whenever a pair of diagonally opposed switches

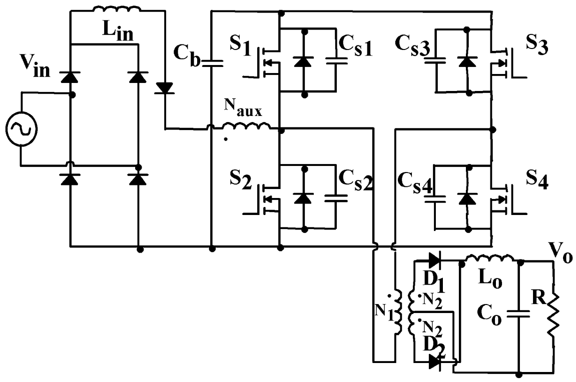

Fig. 16. Single-stage PWM full-bridge converter proposed in [17].

is on, and energy is transferred from the dc-bus capacitor on the primary side. The input inductor current rises during this time. The converter is in a freewheeling mode whenever both bottom switches are off. Energy stored in $L_{\rm in}$ is transferred to C_b whenever the converter is in a freewheeling mode and the input current falls.

A different PWM technique than the standard phase-shift control technique typically used in a phase-bridge converter must be used in this converter. The gating signals of the switches in a converter leg are asymmetrical with the top switch having a pulsewidth of $(1 - D)T_{\rm sw}/2$ (with $D =$ duty cycle and $T_{\rm sw} =$ switching period) and the bottom switch having a pulse width of D $T_{\rm sw}/2$. The gating signals of the switches in a leg are complementary with some "dead-time" added to avoid the possibility of cross conduction.

It was found in [16] that the dc-bus voltage can be reduced if the input inductor is connected to a single bottom converter switch instead of both bottom switches. This reduces the number of times energy is stored in the input inductor during a switching cycle from two to one. Less energy stored in the input inductor means less energy transferred to the dc-bus capacitor, which ultimately means less dc-bus voltage. A further improvement to this converter was proposed in [17] and is shown in Fig. 16. The input inductor of this converter is connected to a single bottom switch through an auxiliary winding coupled to the main transformer. The converter operates in the same manner and with the same gating signals as the one shown in Fig. 15. Input current rises and energy is stored in $L_{\rm in}$ when the switch is on, and the input current falls as inductor energy is transferred to C_b when the switch is off. When S_2 is on, so too is S_3, and a voltage is induced in auxiliary winding $N_{\rm aux}$ with a polarity that causes a reduction in the net voltage across $L_{\rm in}$. Since there is reduction in voltage across $L_{\rm in}$, there is also a reduction in the energy stored in this inductor and, therefore, a reduction in the inductor energy transferred to C_b when S_2 is off. It is the reduction in the energy stored in C_b that causes the dc-bus voltage to be reduced.

Experimental results obtained from an 85–265-Vrms input, 48-Vdc output 50-kHz, 500-W prototype were presented in [17]. The results confirmed that the converter can operate with a dc-bus voltage less than 450 V, an input power factor ranging from 0.84 to 0.92, a maximum efficiency of 87.2%, and with an SCM input current with harmonic components that comply with EN61000-3-2 class D standards for electrical equipment.

B. AC–AC Converters With High-Frequency Output

AC–AC converters can be used as the front-end converters in high-frequency power distribution architectures (HFPDAs) to convert the low-frequency ac utility voltage into a high-frequency sinusoidal output voltage (i.e., 30 $V_{\rm rms}$, 100 kHz). This high-frequency ac voltage can be considered to be a high-frequency ac source to ac–dc point-of-use power supplies (PUPS), which produce various needed dc output voltages and are discussed in the next section of this paper. High-frequency ac sources are used in HFPDAs to reduce their size and weight. They have potential use in space power distribution systems, which need to be high-frequency systems to reduce the overall weight of spacecraft and satellites, and in computer and telecom distribution systems [18]–[20].

These converters are typically two-stage converters with an ac–dc boost PFC converter linked to a dc-ac inverter, and there is motivation to reduce the number of switching converter stages as there is with ac–dc converters. Single-stage techniques for PFC that can be used in ac–dc converters, however, cannot be used in ac–ac converters, whose input and output frequencies are very different, due to nature of these converters. Unlike an ac–dc converter that can either work under DCM, which is load dependent, or CCM, which is load independent, the dc-ac output stage in an ac–ac inverter is always load independent and there really is no DCM or CCM to choose from. Using a purely single-stage PFC approach in an ac–ac inverter will result in a very high dc-bus voltage, even if the input PFC circuit is designed to work with CCM or SCM.

An approach to ac–ac power conversion that uses two converter stages but a simpler control method was proposed in [21] and is shown in Fig. 17. The boost converter in the PFC stage operates under DCM mode with a constant switching frequency and a variable duty cycle. A unified controller is used to control the two stages simultaneously instead of using one controller for the PFC stage to correct the power factor and regulate the dc-bus voltage, and another to regulate the final output voltage for the dc-ac stage. The unified controller regulates the final output voltage, corrects the input current power factor, and minimizes the dc-bus voltage. The circuit design for the controller is simple and very easy to implement, which reduces the cost of the converter.

There is no independent control of the dc-bus voltage because the converter operates with a unified controller. This voltage is, therefore, dependent on the steady-state energy equilibrium at the dc-bus capacitor and varies with converter operating conditions as it does for an ac–dc single-stage converter. This characteristic is similar to that found in the converters discussed in Sections III-A.1 and III-A.2 of this paper. It was determined in [21] that it is better to operate the boost PFC stage with DCM rather than CCM because DCM operation in this particular converter was found to provide better input power factor while maintaining a similar dc-bus voltage level as CCM. The dc-ac full-bridge inverter can be made to operate with constant switching frequency and phase-shift control PWM pattern. The inverter operating with this control pattern can generate the required high-frequency sinusoidal voltage waveform, which is load independent and has very low THD. In addition, all the

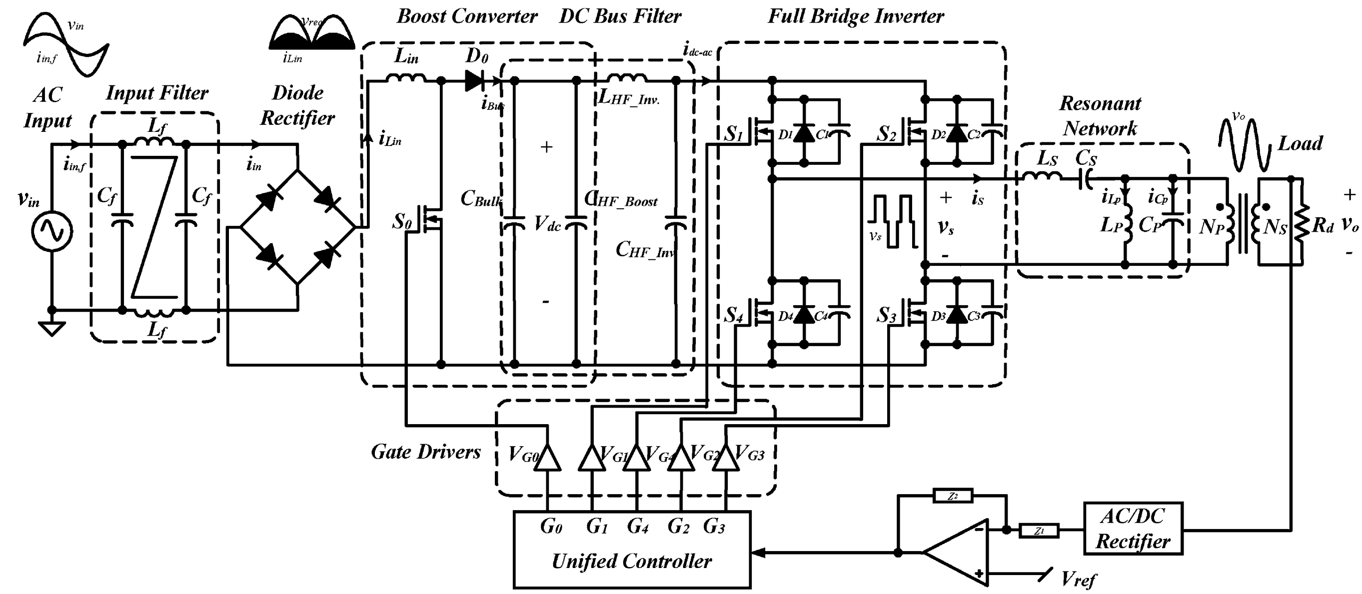

Fig. 17. High-frequency ac–ac converter with unified controller.

switches in the inverter can operate with ZVS if the inverter is properly designed, thus, high efficiency at high switching frequency can be realized.

Experimental results obtained from a prototype of an inverter system built to convert 90–265 Vrms, 60 Hz to 30 Vrms, 100 kHz at 250 W power output were presented in [21]. The prototype inverter was shown to have a maximum input power factor of greater than 0.91, a maximum overall efficiency of greater than 83%, an output voltage THD of less than 5% under all operating conditions, and a dc-bus voltage of less than 450 Vdc under all operating conditions. It was noticed that the maximum dc-bus voltage occurred under high-line light-load conditions, when the amount of energy transferred from the dc-bus capacitor to the load is minimal. It was also found that the converter efficiency was about 5% less under low-line conditions than it was under high-line conditions because there is more current circulating in the input section of the converter under low-line conditions and, therefore, more conduction losses.

IV. AC–DC Converters Operating With a High-Frequency AC Source

High-frequency ac sources are found in HFPDAs, as discussed in Section III-B. These sources can be generated using ac–ac converters to convert the low-frequency utility voltage into a high-frequency ac source, or dc-ac converters, where the original source is dc such as a battery. AC–DC converters in HFPDAs are PUPS that convert the high-frequency ac source voltage into the required dc voltages. Since the maximum utilization of power occurs when the PUPS operate with unity power factor, when the current flowing into them from the source is sinusoidal and in phase with the source voltage, it is very desirable that the PUPS be implemented with some sort of PFC.

The conventional ac–dc PWM boost converter shown in Fig. 2 is not a suitable converter that can be used to perform PFC when the input ac source frequency is high because the ratio of switching frequency to source frequency must be very high to achieve a good power factor. If the input source has a frequency in the range of tens of kilohertz to megahertz, then the switching frequency of a boost converter would have to be in the range of tens, even hundreds of megahertz for it to satisfactorily perform PFC. Since there is no existing device that can switch on and off at such high frequency, a different approach is needed to perform PFC when the input source frequency is very high. The simplest approach is to use inductor–capacitor (*LC*) components to filter out the harmonic components so that only the fundamental source current frequency component is allowed to flow through the input. Since this fundamental component has a high frequency, the size of the *LC* filters that are needed to block out higher order harmonics components can be very small and inexpensive.

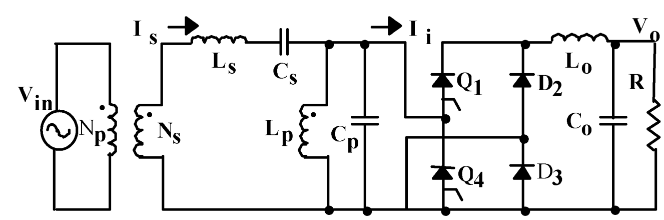

Fig. 18. AC–DC converter for PUPS in high-frequency power architecture proposed in [22].

One of the very first high-frequency ac–dc converters was proposed in [22] and is shown in Fig. 18. The converter consists of a transformer, a double-tuned resonant network consisting of series components L_s, C_s and parallel components L_p, C_p, and a controlled rectifier with two symmetrical switches, Q_1 and Q_4, that are turned on and off to generate a quasi-square current waveform I_i at the input of the rectifier (note that the output current is a smooth dc waveform). The switches can be MOS-controlled thyristors (MCTs). The fundamental component of the current I_i is in phase with the input ac voltage. The resonant network components L_s, C_s, L_p, and C_p, are tuned

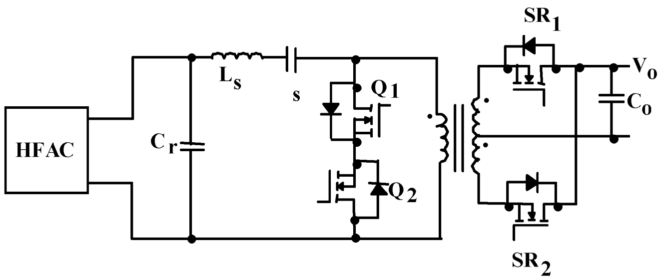

Fig. 19. AC–DC converter for PUPS in high-frequency power architecture proposed in [23].

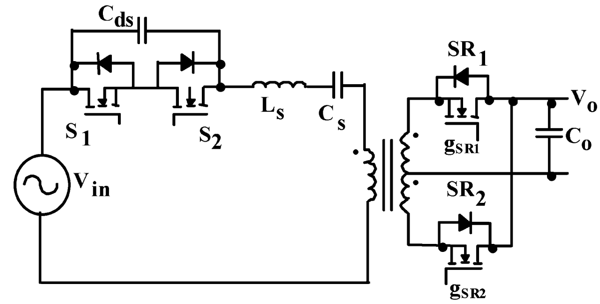

Fig. 20. AC–DC converter for PUPS in high-frequency power architecture proposed in [24].

to the frequency of the ac source. In this way, the series-resonant components L_s and C_s provide low and high impedances, while the parallel resonant components L_p and C_p provide high and low impedances for the fundamental and harmonic components of the current I_i, respectively. This allows the harmonic current of I_i to be filtered out so that the input current is sinusoidal with low THD and near-unity power factor. In [22], experimental results were obtained from a converter operating with a 50-Vrms/20-kHz input and 12-Ω output load. The results confirmed that the converter could operate with an input power factor of greater than 0.98, an input current THD of less than 8%, over a wide range of output voltage control (0%–100%).

The converter in Fig. 18 was designed to be used in high-frequency power distribution systems such as the one proposed by NASA for the Space Station program in the early 1980s. It does, however, have several drawbacks that prevent it from being used in PUPS to power processors in a computer HFPDA. Processors today must operate with very low voltages (i.e., <2 V) at ultra-high speed and with significantly increased density. It is anticipated that future processors will operate at a voltage lower than 1 V, demand currents in excess of 160 A, operate at a slew rate in the order of 10 A/ns, and have more than 4000 input/output (I/O) connections. The converter shown in Fig. 18 does not have transformer isolation, and it is very difficult to step down the voltage to the very low levels that processors require. Moreover, it is difficult to implement the converter with SR MOSFETs instead of diodes, and the conduction losses caused by the output diodes conducting very large output current will be considerable.

A high-frequency ac–dc converter that addressed these concerns was proposed in [23] and is shown in Fig. 19. The converter consists of a resonant tank with components L_s, C_s, and C_r, two main switches to control the output voltage, Q_1 and Q_2, a transformer to match and isolate the load, synchronous rectifiers SR_1 and SR_2, and output filter C_o. The resonant circuit converts the voltage source into a current source, and ensures that the input current is in phase with the source voltage and has very small harmonic distortion under all load conditions.

The main switches are MOSFETs and are connected back to back to form a bidirectional switch. The purpose of these switches is to control the amount of output current needed to be rectified to achieve the desired output voltage and current. Current is diverted away from the transformer and the load when the switches are on, and the switches are turned off when the current flowing through them reaches zero. The amount of current diversion is dependent on the length of time that these switches are on. The resonant network components are off-tuned to the source frequency so that they provide inductive sinusoidal current with near-constant amplitude. The input parallel capacitor is used to compensate the inductive power factor of the series branch so that a near-unity input power factor can be achieved. The series branch also offers very high impedance to harmonics currents to keep the input current distortion to a minimum.

Experimental results obtained from a 28-Vrms/1-MHz input, 1.6-Vdc/20-A output prototype in [23] confirmed that the converter can operate with a near-unity power factor. Simulation results also showed that the converter could produce output voltage overshoots and undershoots of about 5% when the load was varied from full load to 10% load and vice versa with a slew rate that was about 1 A/ns, when a 480-μF output capacitor was used. The main converter switches, however, turn on with hard switching, which creates switching losses. The converter shown in Fig. 20 was proposed in [24] to overcome this drawback.

The converter consists of a bidirectional ac switch made up of switches S_1 and S_2 with a capacitor C_{ds} across it (which can be the combined switch output capacitance), a series-resonant network with components L_s and C_s, a transformer, two synchronous rectifiers, and a capacitive output filter. Output voltage control in this converter is performed by the ac switch, which acts as a switch-controlled capacitor so that the resonant frequency of the primary-side circuit can be changed even though the converter switching frequency is fixed. The equivalent value of the switch-controlled capacitor is dependent on the duty cycle of the PWM signal.

Both converter switches can operate with full ZVS. For example, if both switches are on, then, at some time $t = t_0$, switch S_1 is turned off and S_2 is kept on, with capacitor C_{ds} acting as a snubber to reduce the turnoff losses of switch S_1. At $t = t_0$, current starts to flow into capacitor C_{ds}. Since C_{ds} is part of a circuit along with C_s and L_s, the current will rise then fall to zero, then reverse direction. The negative resonant current will discharge C_{ds}, then flow through D_1 (the diode across S_1) and S_2. While the voltage across C_{ds} is zero, S_1 is turned on with ZVS, and the negative current is now flowing through the ac switch S_1 and S_2. Switch S_2 can turn on with ZVS in a similar manner.

Experimental results obtained from a 28-Vrms input 1.5-V output 30-W 1-MHz prototype were presented in [24]. They confirmed that the converter can operate with ZVS with the output load ranging from approximately 10% to full load, with an efficiency of 82.9% at full load.

V. Conclusion

In this paper, single-stage converters were classified according to the input ac source frequency and the existence or absence of a large bulk capacitor in their dc link. For each of the converter types presented in this paper, the issues associated with each type were discussed, various approaches were examined, and experimental results for particular converters were discussed. The key points of the paper can be summarized as follows.

1) Resonant and PWM ac–dc converters without a large dc-link capacitor can operate with a near-unity input power factor and provide regulated dc voltage. The resonant converters provide higher power levels (up to 3 kW) than the PWM converters (up to 1 kW); however, the resonant converters operate with variable frequency while the PWM converters operate with fixed frequency. The resonant converters are preferred in all the applications except where frequency synchronization is required. The outputs in either type of converters carry a large low frequency current ripple and thus require large filters. They are, therefore, suitable for online ac UPS systems or in some batteryless offline telecommunication systems to convert ac input voltage to −48-V dc output voltage for downstream converters.
2) Single-stage ac–ac converters that produce a low frequency trapezoidal output voltage can be implemented at power levels up to several kilowatts with very high input power factor. These converters exhibit very high efficiency and are suitable for new hybrid fiber coax networks and existing cable TV applications.
3) Single-stage single-switch-type ac–dc converters with a large dc-link capacitor provide regulated and low-ripple dc output voltages with input power factor and current harmonics that satisfy regulatory agency standards. These converters are practical to implement up to 150-W power levels for universal input voltage range (90–265 V ac), and up to 250 W for restricted input voltage range (90–135 V or 170–265 V ac).
4) Single-stage full-bridge-type ac–dc converters with a large dc-link capacitor provide regulated and low-ripple dc output voltages with input power factor and current harmonics that can satisfy regulatory agency standards. These converters are practical to implement up to 500-W power levels for universal input voltage range (90–265 V ac), and up to 1 kW for restricted input voltage range (90–135 V or 170–265 V ac).
5) AC–AC converters with built-in PFC that produce a high-frequency sinusoidal output voltage are practical to implement up to power levels of 250 W with universal input voltage range (90–265 V ac). These converters are well suited for high-frequency ac architectures in future desktop computers.
6) Single-stage resonant ac–dc converters operating from a high-frequency ac source can achieve near-unity power factor, high efficiency, and regulated dc output with very low ripple. These converters are well suited for high-frequency ac architectures in future desktop computers, servers, and telecommunications, or, in general, for powering the low-voltage semiconductor technology of the future.

Acknowledgment

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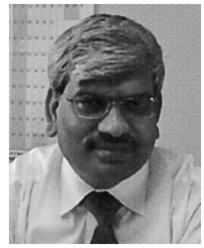

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