Annotated Confirmation Report

Investigation of Power Conversion and Control Scheme for High Frequency AC Power Distribution System

The Hong Kong Polytechnic University

Investigation of Power Conversion and Control Scheme for High Frequency AC Power Distribution System

Include the name of the supervisor and the date on the title page.

Include the following:

i. An abstract.

ii. Acknowledgements

iii. A table of contents

iv. A list of tables and charts.

v. A list of abbreviations

1. Introductions

High Frequency AC (HFAC) power distribution system concerns the delivery of power at multi-kHz frequency via electric cables. Early work on HFAC has demonstrated the many potential benefits of HFAC systems. We firstly discussed the advantages and disadvantages of HFAC system, emphasis the shortage for application extension, and then give a detailed proposed study content of HFAC distribution system. The typical HFAC distribution power system shows in Fig,l.

✓Explains key terms
✓Explains importance of topic using present perfect, e.g. "has demonstrated"
✓Outlines content of report
✓Uses figure to show example of system
Also mention how the report is organized, i.e. Section 2 describes…"

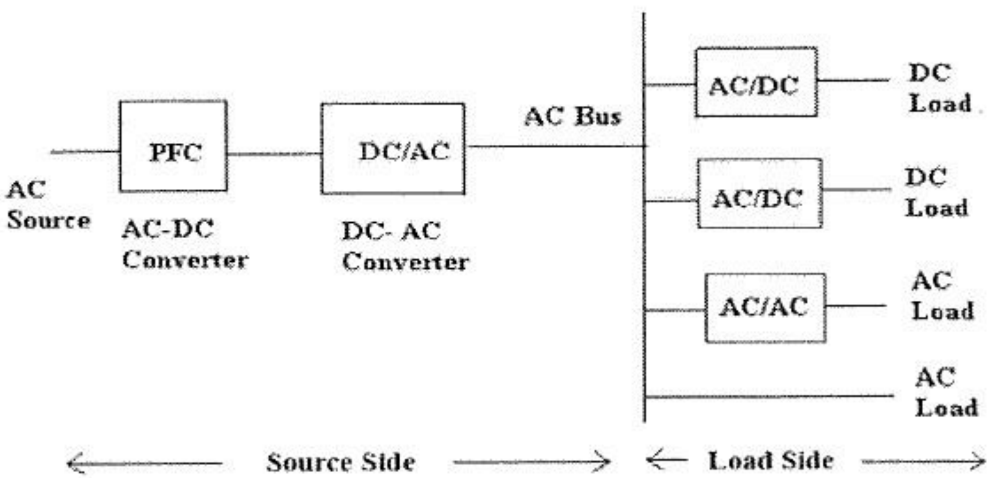

Fig. l Typical HFAC distribution power system

Compared with traditional AC and DC distribution system, the merit of HFAC is distinct; including flexibility to meet different voltage levels, ease of electrical isolation using high frequency transformers, as Well as the prospect of significant savings in component size, count and weight. High frequency operation can also improve the dynamic response, and reduces or eliminates acoustic noise. Despite the many perceived benefits, the application of HFAC was still rare. The main disadvantage contains the additional challenges of higher EMI and higher crosstalk, skin and proximity effect losses in cable, as well as difficulty of PFC and Harmonic compensation. In the view of deficiency and challenge, the application of HFAC is limited to confined field.

Refer to the studies that have previously discussed these points, i.e. "...and Harmonic compensation [1]".

2. Existed Application of HFAC

Section Two is the review of existing knowledge. Often it is a review of previous studies. Here it is a review of existing application. All reviews should include references to other research, comments on the strengths and weaknesses of applications, ideas and studies.

- **Space Application**

✓Gives clear subheading.

Use 'existing' to refer to current applications.

Better to use further subtitles than bullet points, i.e

2. Existing Application of HFAC

2.1 Space Application.

The initial application of HFAC is proposed by NASA Lewis Research Center for space application in 1983, and the frequency of NASA system is from 400l-lz to 20K Hz. NASA Glenn Research Center funded development of a 440 V, 20k Hz AC power system that is flexible, versatile, and transparent to user equipment with high efficiency and low mass[l]. The issues of 20K Hz system are to reduce EMT and cable loss, which have been considered through new cable design with lower transmission losses. The cable was designed and developed by Induction General lnc., initially with flat Litz braids, which were later replaced with flat solid copper conductors. The cable must also have low inductive reactance to minimize voltage drops and radiated magnetic

✓Provides references for information cited

Leave a space before the reference, i.e. "mass [1]" rather than "mass[1]".

fields. NASA's overall conclusions from the studies on AC versus DC in the late 1980s are summarized in Table 1. The 20K Hz system gradually became the main stream in spaceship instead of 400 Hz.

DC	400 Hz	20 kHz
Mature power converter and switchgear in low voltage	Mature technology used in aircraft and submarines	New technology to be developed
Heavy power conversion	Competitive with 20 kHz system	High efficiency, and lower mass per kW
Fewer series component, hence more efficient	Transformer coupling to loads can improve efficiency	Loads transformer coupled to 20 kHz, simplifies LPC
Safer for crew	Simpler protection	Simpler protection
Low EMI	Manageable noise	Inaudible noise
No skin effect	Skin effect loss	Skin effect and dielectric loss

Table.l AC versus DC in Space

Unfortunately, the final adoption of international space station is much lower power levels with 160 V/l20 V DC, instead of440 V/20 kHz AC system.

Give references for all information referred to in the report, i.e. Table 1 AC versus DC in Space [1]

- **Computer and Telecommunications**

In a similar way with the space systems, power distribution in telecommunications and computer has essentially been in the DC domain. In order to satisfy future requirements of ever increasing load levels, higher complexity, higher reliability and compactness, HFAC is an alternative means of power distribution to satisfy requirements.

✓Refers to previous section, i.e. "In a similar way…"

Highlight the main point of the paragraph clearly, i.e. "Waveform and adjustment are important considerations in computers and telecommunications applications."

The waveform selection and adjustment is studied in computer and telecommunications application, whereas the traditional disturbance influence in other applications can decrease and easy to deal with through line connection of board level. Although a sine waveform has the lowest harmonic content, it is complex to ensure sinusoidal waveform with low harmonic distortion and good power factor at all load ranges. Using a trapezoidal Waveform would simplify the converter design to achieve a satisfactory result. Although the harmonics would not be as good as a pure sine wave, the harmonics could be limited to an acceptable level by controlling the soft transition times of the trapezoidal waveform.

A price comparison of a typical DC-DPS system versus an AC-DPS system at 600W is shown in Table 2, with a 37% overall system cost saving (with a 55% reduction in components cost for the Load Modules) for the AC—DPS.

✓Refers to Table 2 in the text, i.e. "is shown in table 2."

	DC Distributed Power System 600W	*AC Distributed Power System 600W*	*Absolute Price Difference*	*% Price Difference*
Front-End PS Transfer Price,	*$214.88*	*$193.98* *(-$11.802 component cost)* *(-$9.099 labor cost,2.585h x 3.52/h)*	*$20.90 less*	*9.73% less*
Six 100W DC/DC or AC/DC PS Transfer Price	*$52.63 x 6 = $315.78*	*$23.63 x 6 = $141.78* *(-$17.21 component cost per unit)* *(-$11.79 labor cost, 3.35h x 3.52/h)*	*$174.00 less*	*55.10% less*
Total Price	***$530.66***	***$335.76***	***$194.90 less for an AC DSP***	***36.73% less for an AC DPS***

Table. 2 The Price comparison for typical 600W DC—DPS and AC—DPS [2]

The first known case of an HFAC Distributed Power Architecture (DPA) implementation in commercial product was found in 1994, by Hewlett Packard in their HP70000 series spectrum analyzers [3].

- **Automotive and Motor Drives** [4-6]

HFAC not only can be used in propulsion system of electrical vehicle, also can be used in many other auxiliary systems.

> 💡 Provide references in the text next to the information they refer to rather than next to the subheading.

However, the EMI and transmission loss need more consideration for EV applications. Kokes and Daimler-Benz already reported on a 25 kHz ITFAC application using square-wave voltage with variable duty sinusoidal current link voltage. However, as in aerospace, the automotive market has not adopted HFAC, partly due to industry inertia, and partly due to the fact that ITFAC still has significant issues of EMI and losses.

> 💡 Give date when giving the name of a study, i.e. "Kokes and Daimler (2011) reported…".

> 💡 Give the full name of an organization the first time it is used and introduce the abbreviation.

As to auxiliary systems, at least three types applications, which are in-car electronics, actuation and lighting, can benefit from HFAC system, the complexity of auxiliary electronics contains power level and load types, which is easy to be solved by HFAC transform and electrical insulation. Moreover, the weight of EV, which can be reduced greatly through HFAC, is a key factor to influence mileage range. To overcome the EMI and loss issues, the HFAC distribution structure can greatly push the progress of EV.

> ✓ Provides clear list of applications.
> 💡 Also give an example of the applications, i.e. "in-car electronics such as …"

The popular AC frequency for EV is 50kHz, and the possible HFAC auxiliary electrical system is shown in Fig. 2.

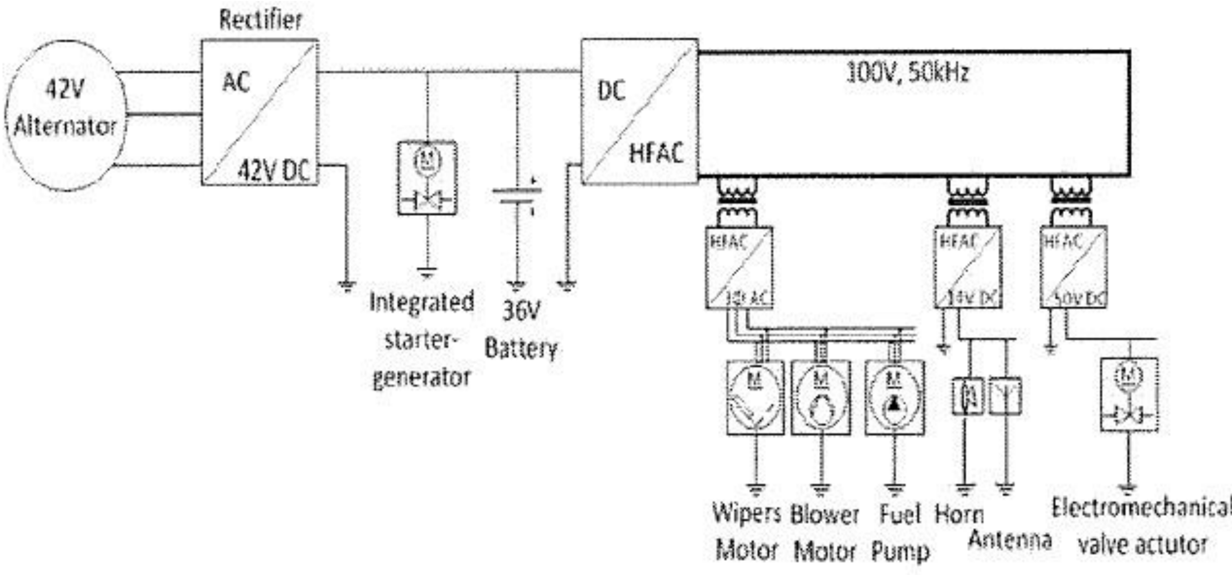

Fig. 2 The possible HFAC auxiliary electrical system [6]

- **Microgrids**

The power distribution application recently emerging is microgrid. A microgrid consists of small power sources called microsources, which are usually derived from renewable power sources such as micro wind turbines, solar panels and fuel cells. Building services loads, such as compressor motors, lighting, and other interface, can be integrated into HFAC as the load. The main advantages for application of I-LFAC are ease to improve power quality at high frequency, less acoustic noise, ease to improve luminous efficiency, and reduction of harmonic ripple current in electric machine.

✓Explains importance of microgrids
✓Defines microgrid
✓Gives example
Give a reference for the source of this information.

Organize the section by using a separate paragraph for the advantages and explaining these advantages with examples

Because the long transmission distance to connect different power source and load, the frequency of AC need be carefully decided to reduce EMI and power losses. The optimal frequency for microgrid could be less than l kHz. The use of 400 Hz power sources is widespread in the military and aircraft industries. A 500 Hz. power system is given for microgrid distribution design [7-8].

In order to ensure the stability of grid voltage and compensate the load influence in high frequency system, some new controllers are required, including Universal Power Quality Conditioner (UPQC) and Universal Active Power Line Conditioner (UPLC)[5]. The UPQC is used to compensate load current harmonics from non-linear loads and voltage distortion from source non-linearity, and provides power factor correction. UPLC is used to control the power flow between the microgrid and the main grid, and also to compensate the current harmonics due to utility connection. Both the UPQC and UPLC controllers can use p-q theory to reduce the computation time needed for performing the control action.

✓Provides clear topic sentence.

✓Introduces key systems

✓Explains advantages of system

End section 2 with a summary of what has not been researched. The 'gap' in the knowledge of the topic. Then state how your study will research the 'gap'.

In consideration of the existed HFAC application, what are our study items in further PhD phase:

> Describe what work has already been done in your PhD in section 3 (methods used or research design completed) and section 4 (Findings you have so far achieved). Future work is normally included in Section 5 with a timetable.

- Parallel operation of HF inverter

  It is difficult caused by high dynamic variation of magnitude and phase and few report exist in the field.

- Input parallel and output series (IPOS) connection

> Explain what has not been studied as part of your description of existing knowledge.

  No study to expand the power in HFAC system using IPOS.

- Improved control method

  It is difficult to control high frequency resonant inverter because of the perturbations from input line, load and parameter tolerance.

- Multi-level high frequency inverter

  Multi-level inverter can effectively solve load factor in resonant inverter, however the cost reduction need further study.

- Soft-switching and PFC for high frequency inverter

  New soft-switching topology with PFC to accomplish the conversion from low frequency AC to high frequency AC.

- Other Possible Further Study

Therefore, the subsequent portion would discuss these items one by one to scheme the research roadmap.

3. Modified Modulation for high frequency resonant inverter in parallel

To compare with other topologies, the single stage resonant inverter with full bridge phase-shift modulation has a simple structure and low cost with fewer components, but the power integration through parallel output is difficult for it. The single stage PSM resonant inverter contains a switching network and a high-order resonant tank, in which the switching network converts the DC voltage to quasi-square waveform, and high-order resonant tank not only filter the harmonics in the quasi—square waveform, also provide the zero voltage switching (ZVS) conditions [9]. The different series and parallel resonant tank including two, three or four energy storage components was discussed, different tank structure has different application field. For instance, the resonant tank with two energy storage components has been used for DC/DC converter; and the one with three energy storage components has been used for resonant inverter of high-intensity-discharge lamp ballasts. To compare with the others, the resonant tank with four energy storage components can provide the sinusoidal voltage with less THD and more flexible capacitor and inductor group for ZVS. Full bridge structure can provide the larger power grade with less switch stress; PSM is easy to provide the ZVS through

State the main point of a sentence first, i.e. "Power integration of the single stage resonant inverter has a simple structure".

✓Gives clear example, i.e. "For instance…"

Divide ideas into shorter paragraphs.

resonance between parasitic capacitor with tank inductor with fixed frequency. Therefore, the single stage resonant inverter with full bridge PSM is preferred solution for HFAC PDS.

Although the HFAC power distribution system was proposed decades ago, only limited application samples are available currently caused by transmission loss of high frequency signals, power expansion issue, high EMT, and etc. The basic control strategy based on frequency analysis has been studied through algorithm combination of feedforward and feedback to obtains good dynamic and steady performance; however it is impossible to solve power expansion issue, because the most popular way of power expansion is to integrate the multiple inverters through parallel connection, which have to face the synchronization of amplitude and phase to avoid the current circulation. Although multiple inverters operation through parallel connection has many merits, the direct parallel connection for high frequency inverter is a disaster for designer to minimize the current circulation. A symmetrical phase-shifted modulation was presented to eliminate the phase discrepancy from amplitude regulation in parallel resonant inverters, the uncontrollable phase still lead to the circulation current, unwanted power losses and device damage. Current sharing control (CSC) algorithm based on average magnitude and phasor transformer to minimize circulation current need current sampling besides the voltage sampling [10]. If the phase correction and

> Give references for the source of this information, i.e. ..proposed decades ago [4], ...

> Avoid giving lists ending with "and etc". Use "including transmission loss of..., high EMT and a number of other difficulties.

> Avoid emotional language, e.g. "disaster". Better to use formal language, i.e. "problematic".

> ✓ Gives full name and abbreviation first time phrase is introduced.

compensation can be realized in individual full bridge PSM inverter, the output current sharing is easy for implementation. However, the shortcoming confines the application of PSM resonant inverter, especially in power expansion. Because the only voltage amplitude is controllable, instead of amplitude and phase, the existed modulation is not enough for power expansion of PSM resonant inverter with parallel output. The typical diagram of resonant inverters in parallel connection is shown as below.

✓Explains possible solution. e.g. "If…"
✓Highlights limitations, e.g. "However, the shortcoming…"'
✓Explains limitations
✓Illustrates with diagram

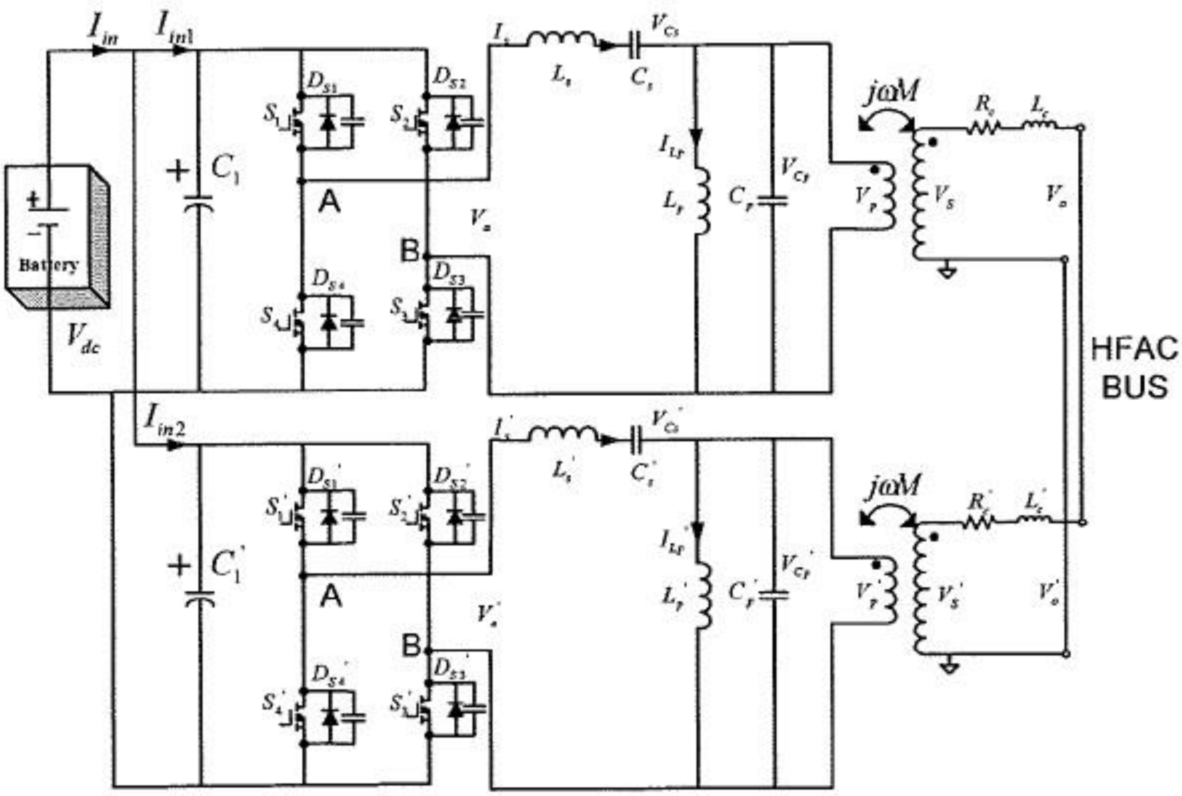

Fig. 3 Typical diagram of resonant inverters in parallel connection

The traditional PSM is to compare the sawtooth waveform with the modulation signal (V_m) to generate

✓Give title describing diagram

the changing phase-shift angle (α) and to control the output magnitude of resonant inverter. However, the conventional PSM has an issue that it cannot get rid of the coupling between magnitude control and phase control, i.e., the magnitude changing leads to the further phase-angle changing caused by this coupling. The traditional PSM structure is shown in Fig. 4a; and the typical waveform for the traditional PSM control is shown in Fig. 4b, in which α is the phase-shift angle between the lead and the lag bridge, and δ is the pulse width of phase-shift amplitude control. From the geometry relationship, the general relation between α and δ is $\alpha + \delta = \pi$; and α is obtained from the modulation signal (V_m) as $\alpha = \frac{(V_{pp} - V_m)}{V_{pp}}\pi$, in which V_{pp} is the peak-peak value of the carrier signal.

Explain where figures are, i.e. "in Fig 4a on the following page".

✓Describes process using present simple tense and passive voice, i.e. "is fixed"

As shown in Fig. 4b, the polarity inversions of the lag bridge is fixed because of the sawtooth waveform characteristics; while the polarity inversions of the lead bridge shifts along with the modulation signal and generate the phase angle α . Therefore, α/2 is the voltage phase shifts result from the magnitude modulation. The amplitude and phase of resonant inverter output in traditional PSM are described as;

Center formulae and number them in the same way as diagrams.
✓ Refers to formula in text, i.e. "are described as"

$$\|v_o(t)\| = \left\|\frac{Z_s}{Z_s + Z_p}\right\| \frac{4}{\pi}\sin(\frac{\pi - \alpha}{2}) \left\|\frac{R_L}{R_L + Z_c}\right\|;$$

$$\angle v_o(t) = \frac{\alpha}{2} + \angle Z_s + \angle Z_p + \angle Z_c; where, Z_s = R_s + jX_s; Z_p = R_p + jX_p; Z_C = R_c + jX_c;$$

Where, Z_S and Z_P are the series and parallel impedance; Z_C is the connection impedance; and R_L is load resistance. The amplitude is decided by phase-shift angle between the two legs (α),resonant tank impedance, connection impedance and load impedance. The phase with respect to the carrier signal is determined by α, as well as phase angle of connection and load. Namely, the phase angle of output voltage not only depends on the passive components, also depends on the magnitude modulation signal (V_m). The symmetrical PSM proposed by Ye present a new approach to eliminate this coupling through triangle waveform carrier signal and proper logic structure changing.

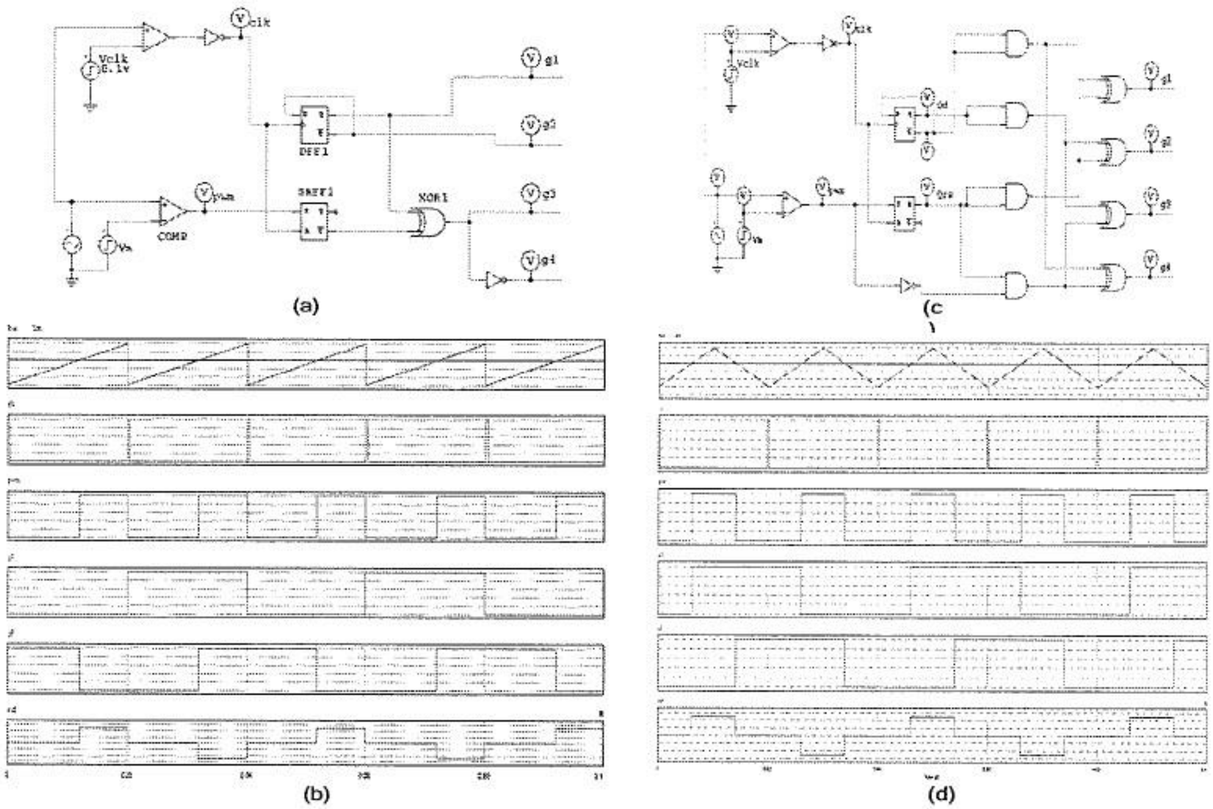

Fig. 4 Traditional PSM and symmetrical PSM

The logic structure diagram of symmetrical PSM is shown in Fig .4c, and the typical waveforms as shown in Fig. 4d are used to demonstrate the logic operations. As shown in Fig. 4d, the triangle waveform carrier with the peak-to-peak voltage (V_{P-P}) is used to compare with modulation signal (V_m) to generate PWM signal. The rising edge modulation trigger the polarity inversions of the lead bridge; while the falling edge modulation trigger the polarity inversions of the lag bridge. In the view of the symmetrical characteristics of triangle waveform, the simultaneous changes in lead and lag bridge lead to the invariable phase angle. If the duty ratio loss caused by delay time and switch dead time is ignored, the phase angle of output voltage can retain precise consistency without the parameters tolerance consideration

✓Describes problem

✓Refers to figure and explains main features in text, e.g. "As shown in Fig 4d" from passive components. Therefore, the phase angle of the output voltage is independent of the modulation signal, which frequently changes to correct the output amplitude against the disturbance from input line and load. The output phase of resonant inverter in symmetrical PSM is described,

$$\angle v_o(t) = \angle Z_s + \angle Z_p + \angle Z_c; where, Z_s = R_s + jX_s; Z_p = R_p + jX_p; Z_C = R_c + jX_c;$$

✓Discusses possible solution

Although the phase influence from magnitude modulation is eliminated, the parallel system is still not perfect, because the parameter discrepancy in individual invert also can generate phase difference and circulation current.

✓Evaluates solution, .e.g. "still not perfect"

ln order to simultaneously control phase and magnitude, a new modulation is proposed as below,

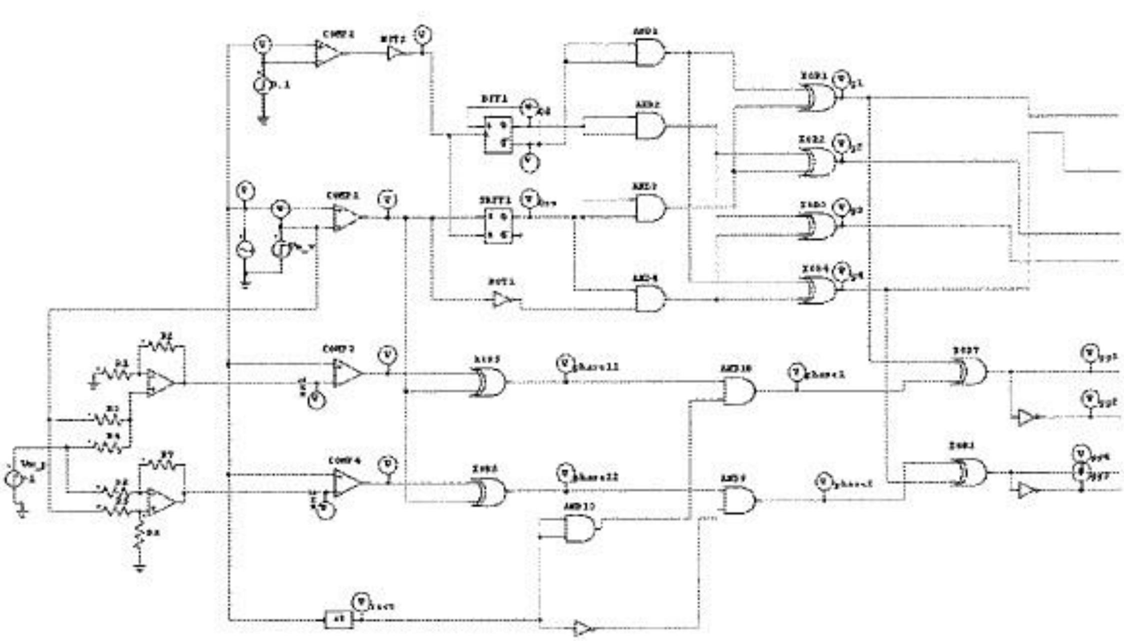

Fig. 5a The logic diagram of new modulation

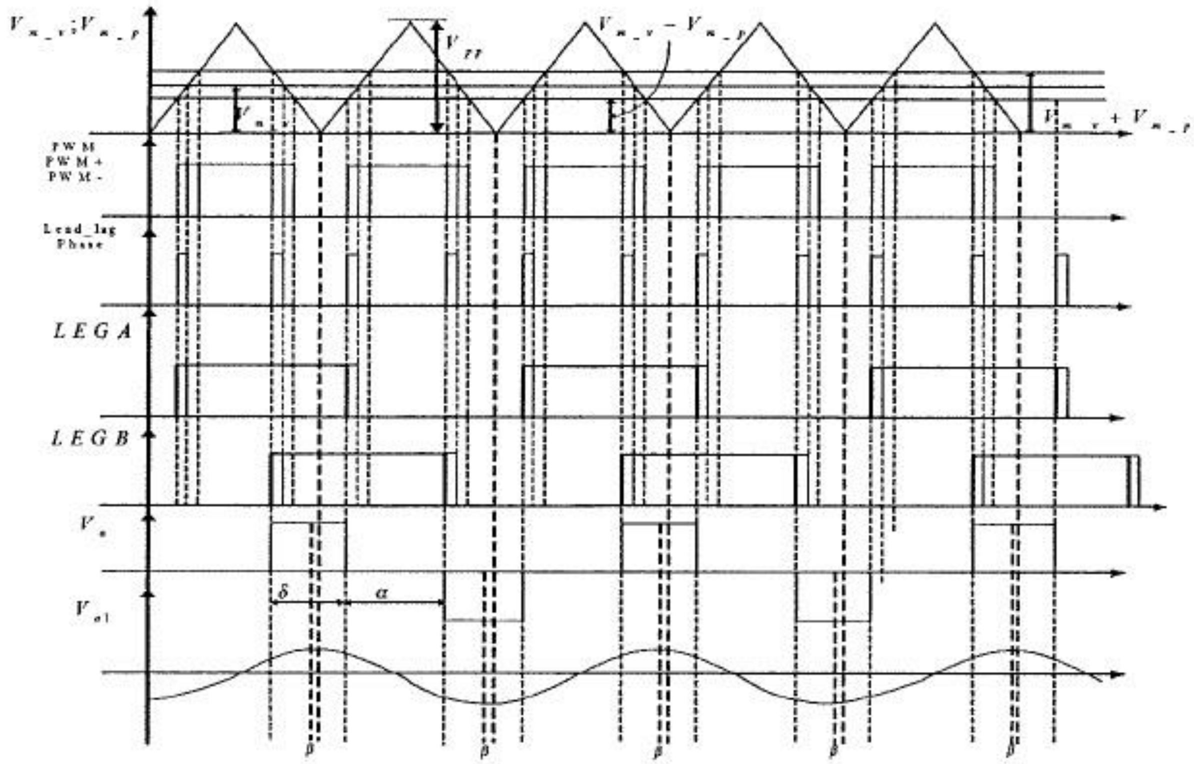

Fig. 5b The typical waveform of new modulation

The typical operation waveform for proposed PSM is shown in Fig. 5b. To compare with the above two modulation, the proposed PSM can be divided into three steps. The first step in proposed PSM is same as modified PSM discussed in last part to generate symmetrical quasi-square waveform output. The second step is the integration of phase angle correction implemented by difference amplifier and non-inverting summing amplifier.

> Paragraph the section more clearly using one short paragraph for each step
>
> Avoid inaccurate phrases e.g. "in the last past". Better to give a section number, i.e. "in section 3.3…"

The output of them is $V_{m\_v} + V_{m\_p}$ and $V_{m\_v} - V_{m\_p}$ to compare with triangular waveform carrier and generate PWM signal with phase angle correction(PWM_sum and PWM_diff). V_{m_v} is the output of magnitude controller, and V_{m_p} is the output of phase controller. The third step is to select the proper phase angle correction signals (phase1 and phase2) to shift the lead and lag bridge. Because the phase angle correction signals shift the lead and lag bridge simultaneously, the pulse width. However, the output phase of resonant inverter in proposed PSM is changed as below,

$$\angle v_o(t) = \angle Z_s + \angle Z_p + \angle Z_c + \Delta\alpha; where, Z_s = R_s + jX_s; Z_p = R_p + jX_p; Z_C = R_c + jX_c;$$

Where the phase angle correction($\Delta\alpha$) is used to compensate the phase discrepancy caused by component tolerance.

In order to implement phase control, the pulse phase sampling is the first step to retrieve the phase discrepancy between outputs with reference voltage. The two traditional phase sampling methods are: the one is multiplier operation sampling; the other one is comparator operation sampling. To compare with the comparator operation method, the multiplier operation sampling is easy to be implemented by analog device without arithmetic operation, so it is the optimal solution in proposed system. If the voltage reference for resonant inverter output is $v_r = V_r \sin(\omega t + \varphi_r)$, which has amplitude V_o and phase angle φ_r. The output voltage of the resonant inverter is $v_r = V_r \sin(\omega t + \varphi_r)$, which has amplitude V_0 and phase angle $\varphi_o(t)$. To compare the voltage reference and output voltage, the phase angle φ_r is regarded as a constant, while the phase angle $\varphi_o(t)$ is a time-varying in transient state. The control requirement is that output voltage v_o must follow the voltage

Use a subtitle than start each section, i.e. "3.3 Implementation of Phrase Control"

✓Uses comparative language e.g. "To compare the...", "as closely as..."

reference v_r as closely as possible, namely that $V_r = V_o; \varphi_r = \varphi_o(t)$. The former equation can be ensured by voltage loop; while the latter one need be implemented by phase angle control. As the magnitude control does, the control quantity error is retrieved by two signals subtraction as below.

$$\varphi_e(t) = \varphi_o(t) - \varphi_r \quad (1)$$

The premise is to assume the inverter output owns an ideal sinusoidal characteristic, i.e., the harmonics in quasi-square waveform is perfectly filtered by resonant tank; and only the fundamental frequency component exists in inverter output. Actually, the appropriate resonant tank parameter can provide the excellent filter performance. According to multiplier operation sampling method, the multiplier operation is applied on the reference and output signal; and the multiplier operation output is

Place adverbs next to the verb, i.e. The appropriate resonant tank can actually provide"

$$v_{ep}(t) = V_o \sin(\omega t + \varphi_o(t)) \times V_r \sin(\omega t + \varphi_r) = \frac{1}{2} V_o V_r (\sin(\varphi_r - \varphi_o(t)) + \sin(2\omega t + \varphi_o(t) + \varphi_r)) \quad (2)$$

The DC item in equation (2) is $\frac{1}{2} V_o V_r \sin(\varphi_r - \varphi_o(t)$, which can be linearized near zero. Therefore the DC item is approximately proportional with the phase difference in a small phase difference. The relevant system hypothesis can effectively guarantee a small phase difference in phase control. So the DC item of equation (2) is derived by

✓Numbers equation and refers to it in text

$$V_{ep}(t) = \frac{1}{2} V_o V_r (\varphi_r - \varphi_o(t), when |\varphi_r - \varphi_o(t)| \to 0$$

While the AC item in equation (2) has twice switch frequency, and is filter by low pass filter. Finally, the simple multiplier operation sample for phase error is accomplished by analog multiplier and a low pass filter.

In consideration of amplitude control of resonant converter, some advanced control algorithms have already been proposed, including H∞ control, passivity control, Optimal trajectory control, neural control, and etc. Each control algorithm always need construct a simple and accurate mathematic model. The traditional model for power converter is the small-signal model; and the state-space averaged modeling method is the most simple and frequently-used method. However, it is not valid for resonant converter because of the violation of small ripple assumption. Generalized averaging method using Phasor transformation can construct the available model for resonant converter through Fourier transformation from periodical ac variables in rotary frames to dc variables in stationary frames; however, it makes the model complicated with higher order. The series-parallel resonant inverter is a fifth order system with five state variables including inductor currents and capacitor voltages, so that a tenth order model generated by the generalized averaging method leads to a difficult controller design. Some assumptions for controller design are given as: (1) the output voltage after series-parallel resonant tank only has the fundamental components left to ignore the harmonics. (2)

> Use more precise language than "some", i.e. "a number of…", "a variety of…"
>
> Give the sources of these models and to discuss them i.e. "have been proposed [23], [24], [27].

> ✓Discusses strengths and weaknesses of existing models

> Use more paragraphing. i.e. a new paragraph for assumptions.
>
> Do not include lists as not part of the paragraph.
>
> Avoid inconsistency in lists e.g."(1), (2), (3), Finally". It is better to state "(1), (2), (3), (4)".

small-signal disturbance is appended on the large signal and can be linearized by Taylor Series Expansion; (3) the controllable input voltage as a nonlinear item is attached on the model. Finally, although the nonlinear item still exists, the simplified small signal model is obtained around the steady operation point. According to the obtained transfer functions between controls with outputs based on model, amplitude controller is easy to be designed by frequency domain analysis or other advanced algorithm. The phase angle control also is simple because the phase sampling discussed before has linearized the phase error. We assume the PSM resonant inverter has a fixed phase difference, because the parameter of series-parallel resonant tank and connection impendence both are settled beforehand and are precise. Because the phase angle gain of resonant inverter and phase sampling gain both are constant, a simple controller design of linear system based on small signal and frequency analysis is available for phase angle control to provide a good dynamic and steady performance.

Avoid starting paragraphs with "Firstly". Explain what is first, i.e. "The first stage of PSIM…"

Firstly, the PSIM simulation is accomplished; and simulation object is the proposed modulation method. The typical waveforms at critical points as shown below are given to demonstrate the phase compensation. The bridge voltage of the inverter with the proposed PSM is shown in Fig. 6a to prove the phase correction capability. The corresponding output voltages as shown in Fig. 6b also prove lead and lag compensation of phase.

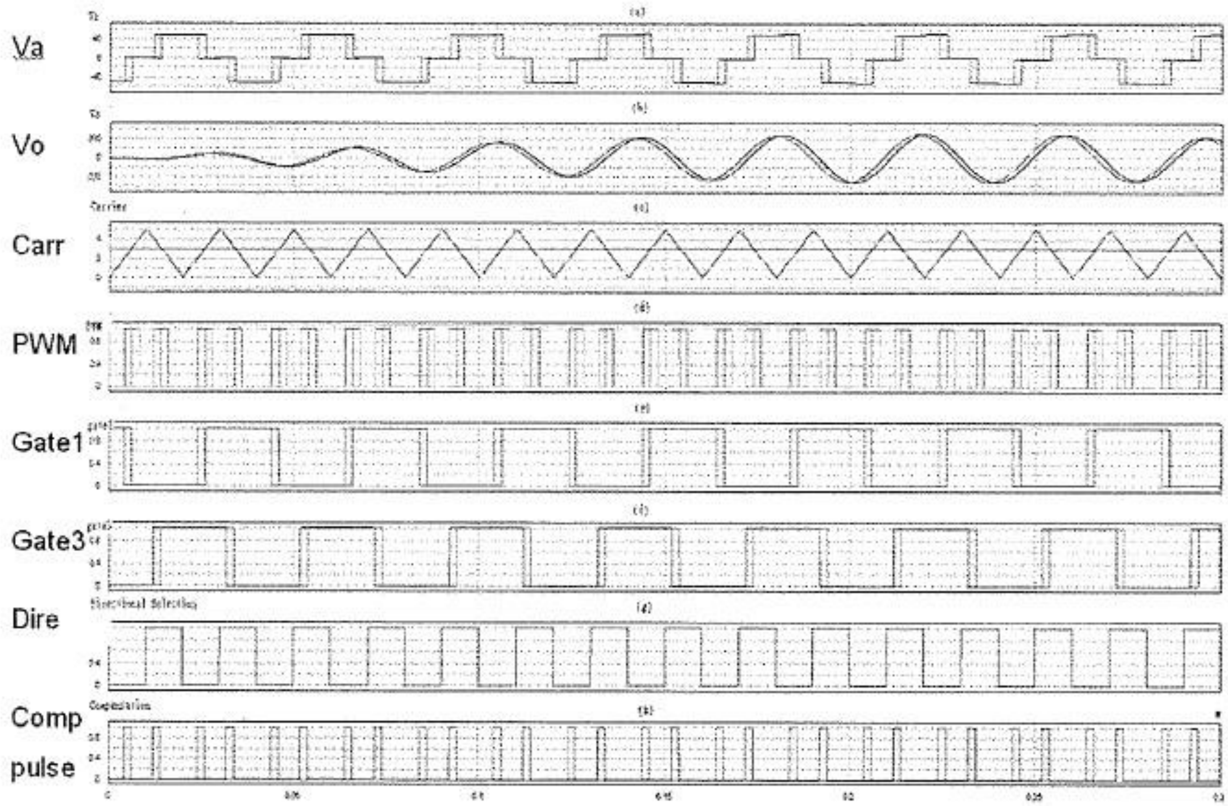

Fig. 6 Simulation Waveform

To verify the effectiveness of proposed modulation method, we set up a paralleled HFAC power source constructed by 2 power modules. The overall controller diagram is set up by LF353, which is a dual operational amplifier with 4 MHz bandwidth operated dual voltage mode. The phase shifted signal is generated by UC3875 because it can interiorly generate the ramp signal and obtain logic comparison. TTL logic output is magnified by IR2l13 to generate the gate driver for IRF530N. In addition, regarding to the ZVS parameter design of resonant inverter in proposed IPOS, the equivalent impedance is different with the

Distinguish work that has been done from work that will be done using tense, i.e. "diagram was set up" or will be set up". Work that is always done by most researchers is described in the present simple tense, i.e. "is set up".

Use passive voice when describing methodology rather than "we", i.e. "A paralleled HFAC power source was set up".

ordinary one. If the module equivalent inductor of primary side is L_r/N^2 (L_r is secondary side inductor and equal to $L_{S2} + L_{P2}$; N is the turn ratio of resonant inverter), the equivalent inductor of primary side is nL_r/N^2 . Hence, the ZVS resonant capacitor for IPOS inverter is 1/n of the individual module (n is the module number in series connection).

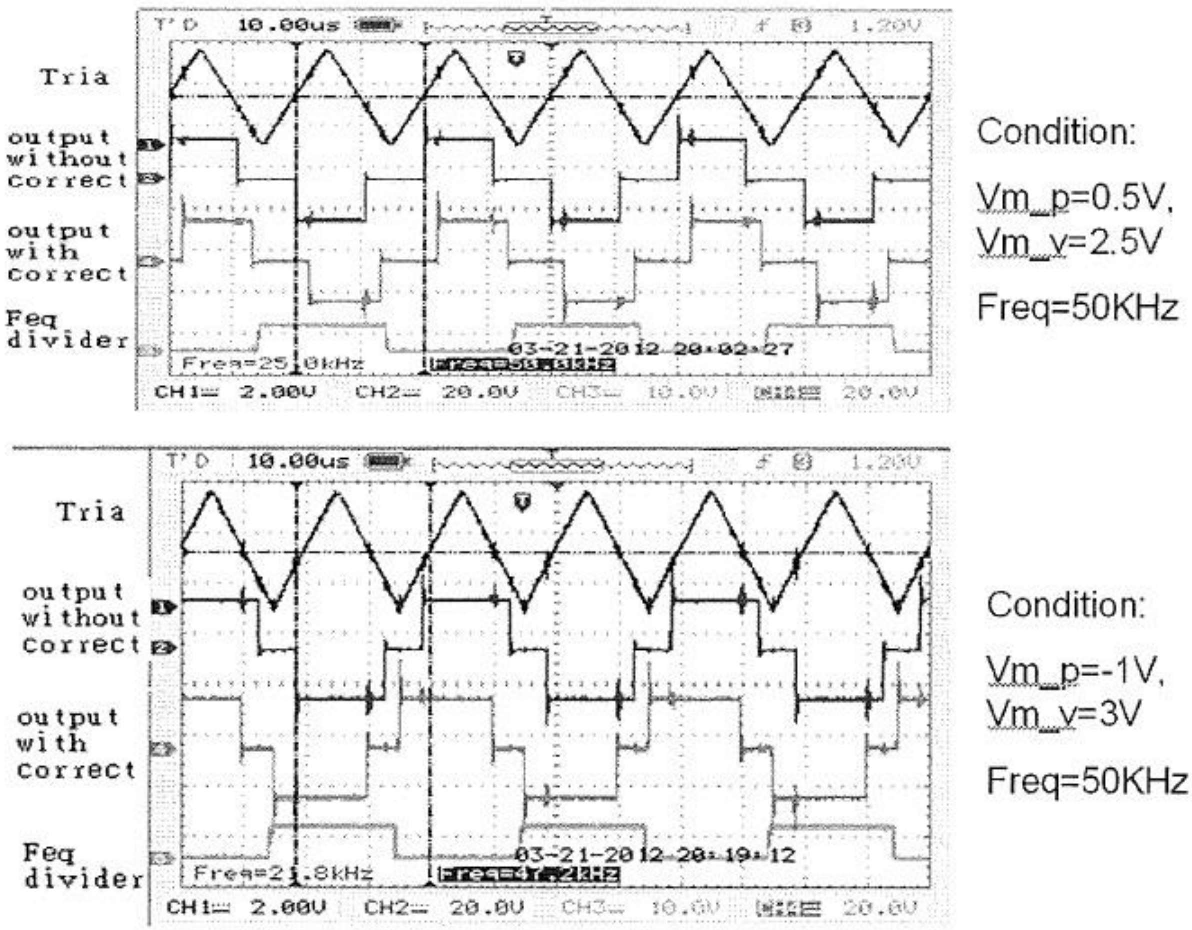

Fig. 7 Experiment Waveform

High frequency Alternating Current (HFAC) caused by its unique advantages has already been applied in many power distribution system (PDS). As the power distribution system with SOHZ or 400112, the phase control of paralleled inverters is complicated in I-LFAC system with over IOK Hz frequency. A few of method including modulation, control and topology are proposed to lessen the circulation current in parallel system. However, it is difficult to precisely guarantee the magnitude and phase synchronization. A new modulation method is proposed to simultaneously accomplish the amplitude and phase control to reduce the perturbation from parameter tolerance and operation condition. The proposed modulation method completely removes the coupling relationship between phase and amplitude, so that the controllers can be independently designed without correlation. The quantitative analysis of proposed modulation in transient and steady state is fulfilled to testify that an appropriate control design can effectively reduce the phase deviation in transient state. Because of the simple modulation and control, analog discrete devices are enough for the cost reduction and the response acceleration. An experiment prototype is fulfilled to prove the effectiveness of the proposed modulation.

✓Uses present perfect tense to describe background, e.g. "has already been applied"

Cite sources of information, i.e. "A few methods…are proposed [66], [67]…

Number sections in a logical manner. The previous section and this section should be numbered,

3.1

3.2

Finish a section with a short summary.

Clearly state what work will be done in the future and what work has already been done at the end of the section

4. Novel Input parallel output series structure and decouple control scheme for HF resonant inverter

Voltage sampling factor, G_{shi}, is the transfer function of Intermediate voltage sharing controller, G_{sh}, is the transfer function of intermediate voltage controller, G_O is the transfer function of output voltage controller, and Kc is the feedforward factor from outer voltage loop to intermediate voltage loop. Intermediate voltage sharing loop is to keep the output voltage balance for each DC modules with serial connection; the intermediate voltage loop is to ensure the output voltage of DC converter stable to decrease the impacts for backend inverter; the output voltage loop is to guarantee the HFAC output with stable amplitude and lower THD. The proposed serial-parallel connected system turn the amplitude and phase control into the exclusive amplitude control to simplify the power expansion in HFAC system; meanwhile, the HFAC voltage outer loop is also a DC comparison, i,e., HFAC output(V_O) is rectified and filtered to DC feedback($V_{of)}$ to generate error value by comparison with DC reference(V_{ref}). The controller loops with DC comparisons can neglect the generation and operation of HFAC signal with high real time requirements, so that the simple 8 bit MCU can fulfill HFAC voltage control with good performance. Meanwhile, the feedforward controller of resonant inverter to compensate the input line disturbance is ignored caused by the stable voltage input; the ordinary P or PI controller is enough for individual converter.

✓Explains process using "to infinitive structures to show purpose, e.g. "to simplify, to compensate" and also more formal ways, i.e. "so that".

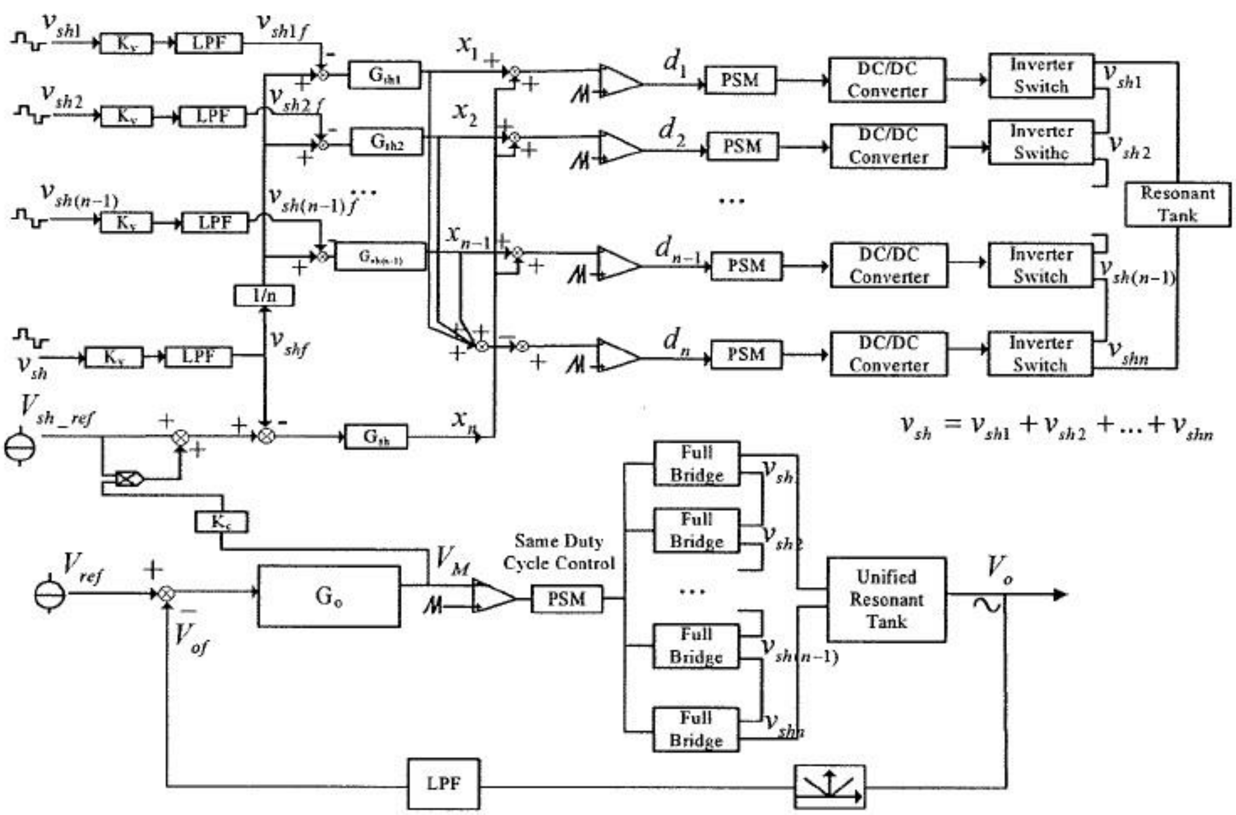

Fig. 9 The control diagram of IPOS structure

Meanwhile, the system is easy for expansion if more modules are required to be integrated into the system, because the three controllers are decoupled and can be design individually. Furthermore, the feedforward compensation for front-end converter from back-end converter can ensure a good waveform quality within a broad operation scopes. In the following parts, each controller design is discussed one by one based on small-signal modeling to facilitate the construction of the interleaved system with series-parallel connections.

Do not overuse linking expressions such as "meanwhile", i.e. "At the same time", "In addition".

✓Explains strengths and possible changes of proposed model

Although the dynamic and steady performances both are significant for power distribution system, the system stability is premise, particularly a system with composite structure. The proposed system is not only a system with serial or parallel connection, also a system with interleaved converters. Therefore, the system need be analyzed from output voltage sharing stability by IPOS connection and stability impacts from interleaved converters. Meanwhile, the designs of feedforward factor also need be considered to maintains the system stability, and enlarge the system operation scopes.

✓Explains motivation for next part of section, e.g. "Therefore the system needs to be ..."

As shown in Fig. 10, V120 is the V_m value under 120 degree δ ; as well as V_{ref} and $V_{sh\text{-}ref}$ both are 5V reference. The resistor and capacitor of DC OVS controller is determined by 20log(R13/R1)=magnitude compensation; $C1 = \frac{1}{2\pi f_1 R13}$; $(10 f_1 \le f_c)$; f_c is the cut off frequency after compensation. The similar method can obtain the parameters of DC output controller including R5, R14, and C2. To transform the HFAC outer controller into $Go(s) = \frac{K(1+\frac{s}{\omega_z})}{s(1+\frac{s}{\omega_p})}$, the resistor and capacitor are determined by $K = \frac{1}{R31(C3+C4)}$; $\omega_z = \frac{1}{R33C3}$; $\omega_p = \frac{C3+C4}{R33C3C4}$

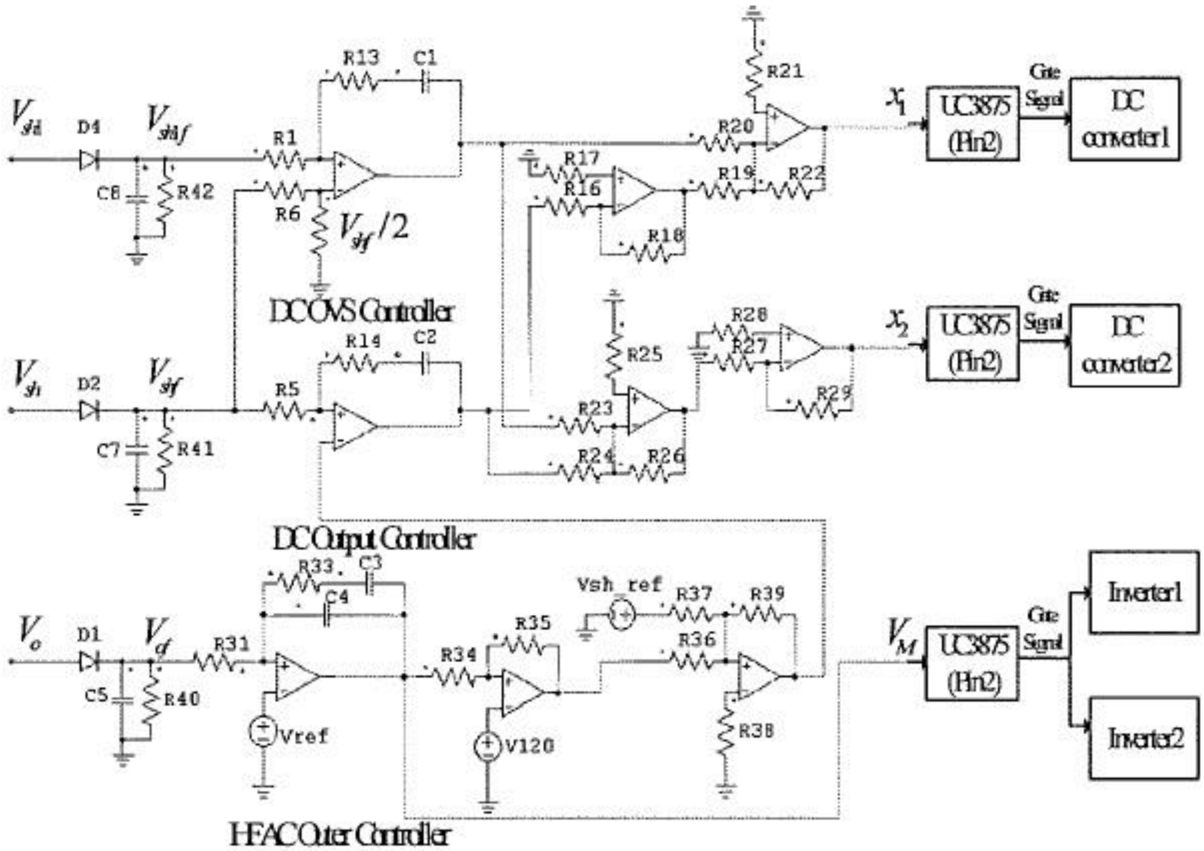

Fig. 10 the circuit schematic of decoupled controller

Firstly, the PSLM simulation is accomplished as shown in Fig. 11; and simulation object is the proposed interleaved high frequency inverter with IPOS integration. The control and output waveforms are given to demonstrate the proposed algorithm. It can be observed the output voltage(V_{out}) and output current (I_{out}) have perfect the sinusoidal waveform in disturbance conditions; the output voltage of middle DC converter (VPl2 and VPl3) can keep stable and simultaneously change for two DC modules; as well as feedback signal, controller output, and comparison difference keep coherence in the whole range. The disturbance are superimposed at 0.007 and 0.015; the load is decreased to 50% at 0.007 and input line increase to 60v Lrom 50v at 0.015. The output curve proves that the

Provide a section reference for Fig. 11.

✓Uses passive voice to show study is objective, i.e. "It can be observed".

proposed algorithm has a certain anti-disturbance capability to ensure the sinusoidal waveform with low THD in the large range of disturbance.

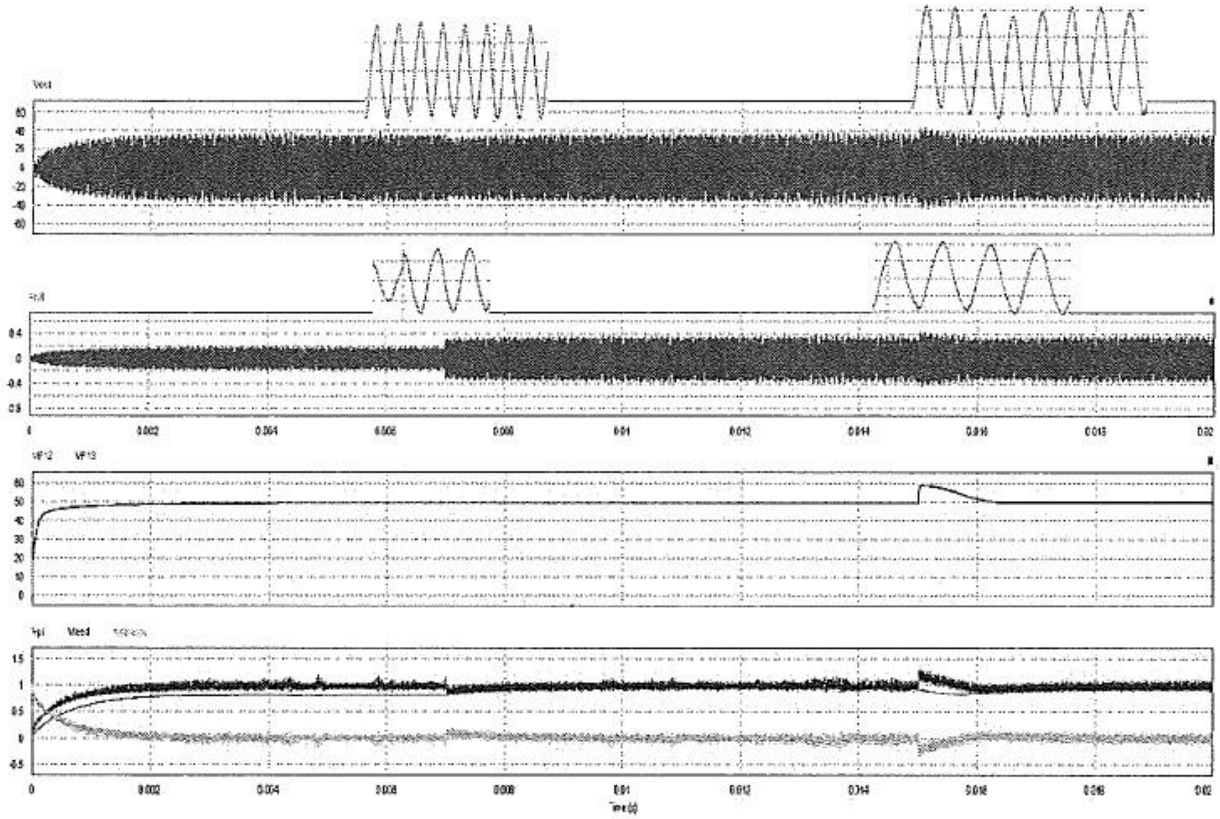

Fig. 11 Simulation waveform

Two 25 kHz full bridge resonant inverter connected with 100 kHz full bridge PSM converter modules are combined through IPOS structure in the laboratory for proposed algorithm verification. According to the selection of series-parallel resonant components, the switch frequency is higher than series resonant tank; and lower than parallel resonant tank to ensure ZVS of full bridge. The input voltage is 40v, output voltage is 30v with rated power of 200w. The controller is constructed by analog components, such as op-amp, resistor and

✓Lists main steps of system and gives key details in description of the system capacitor; and the three controller schematic diagram is shown in Fig. 10. The phase shift signal is generated by UC3875. IRF530N and IR2110 are used as the power switches and gate drivers.

After the controllers are designed, the corresponding steady and dynamic performance experiments are fulfilled to evaluate the controllers. The Fig. 12a shows the basic gate signal, module output and difference of two module outputs in steady state; while Fig. 12b shows the front-end DC output and back-end HFAC output under input line perturbation. As the steady-state waveform shown, the module output closely matches with other modules output through proposed OVS controller. The small ripple difference is easy to be filtered by series-parallel resonant filter.

✓Gives clear topic sentence to outline contents of next part of section.

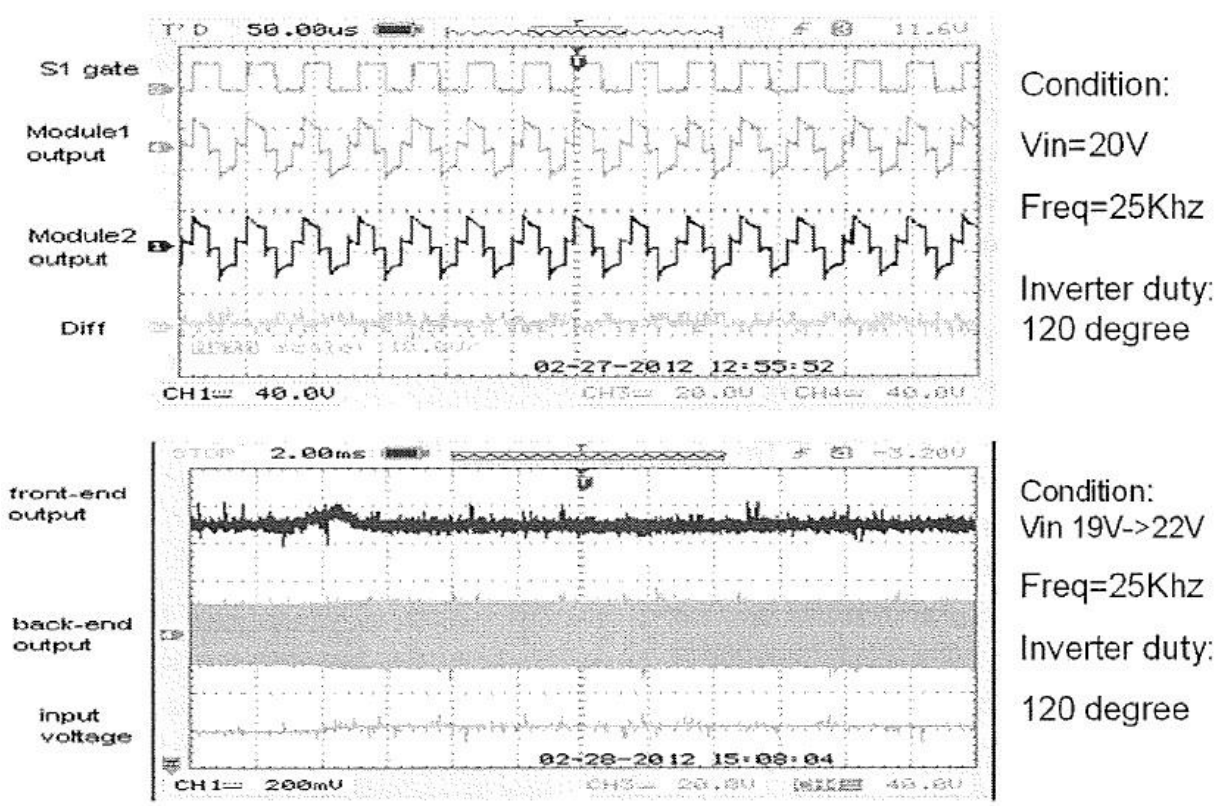

Fig. l2 Experiment waveform

The dynamic-state waveform to demonstrate rapid stabilization is deteriorated by intermediate filter components; so that longer settling time is required. As shown in Fig. 12b, the settling time of DC output is close to 2ms, so that above 50 HFAC cycles are required before entering stable state. To compare with one stage resonant inverter, the dynamic performance becomes tardy for two stage interleaved system; however, proper parameter can reduce the impact from filter. A tradeoff between dynamic performances and ripple suppression need be optimized to achieve an acceptable result.

> Avoid using informal language, e.g. 'tardy". 'The dynamic performance deteriorates" is more appropriate.

> ✓ Uses language "novel" and to highlight this study is original

> Start the summary with a new paragraph.
> ✓ Summarises section and proposed system
> ✓ Highlights advantages of proposed system, i.e. "easy implementation, eliminates, ..."
> ✓ Explains work done already

A novel IPOS structure with interleaved converters is proposed to avoid minimization of circulating current in parallel output, and the decouple controllers design for proposed system have been investigated in this paper. The proposed TPOS structure takes fully considerate the practical configuration in HFAC DPS; power expansion becomes easy for proposed system through proper structure change. Meanwhile, the decouple controller is simple and feasible is introduced to realize flexible and scalable HFAC DPS. The entire DC operation including reference and deviation lead to an easy implementation; the entire control scheme eliminate the mutual interference from other loops; and the proper compensation from correlation factor provide high quality waveform with better against disturbance capacity. A 20 kHz integrated TPOS prototype with 200w power has been implemented to verify the controller effectiveness. The experiments results prove the triple loop controllers with correlation factor compensation provide sinusoidal waveform with better quality within large operation range. Therefore, the proposed LPOS system and controller is a good scheme to propel HFAC DPS into high power and long transmission distance applications.

5. Improved control method [15-18]

The further study will focus on the control of individual resonant inverter, including analog control and digital control. The possible algorithms to control phase and magnitude of resonant inverter are listed as blow,

✓Uses vertical list to display main points

Resonant inverter control

i. Possible Analog Algorithm
    - Robust Controller based on u synthesis
    - Two DOF (Degree of Freedom) PID
    - Other Frequency domain method

ii. Possible Digital Algorithm
    - High order Sliding Mode (Fifth order)
    - Passivity control
    - Boundary control
    - Internal Model control

Use more tentative language when discussing advantages, i.e. "appears to be a good scheme".

Present the benefits of the proposed scheme more clearly earlier in the introductory section.

To compare with digital controller, the analog controller is more suitable for high frequency AC signal, because a high dynamic response is required for controller. The digital controller has the sampling delay and quantization error, both of which can greatly influence controller performance. If the frequency of HFAC signal is 50 kHz and the sampling delay is 1 microsecond, the sampling delay can generate phase delay with l8 degree, which is unacceptable for high performance controller. Therefore, high performance microprocessor is required, such as DSP TMS32028335 to reduce the sampling delay. Simultaneously, the advanced control algorithm required digital microprocessor to accomplish the calculation, so it is a contradiction to retrieve a tradeoff between the high speed control and high performance control.

✓Compares and contrast two methods of control using effective language, i.e. "to compare, both, if, simultaneously"

For instance, to replace the controller with nonlinear sliding mode controller (SMC), the voltage regulation can have better capability to deal with large signal disturbance. Moreover, SMC can effectively handle model inaccuracy, perturbations from line and load, and parameter uncertainties through presetting sliding plane, so that the robustness of the control system can be guaranteed. The conventional method of SM controller is designed by hitting condition, existence condition and stability condition. The implementation of signum function with state variable trajectory in hitting and existence conditions has a very high and uncontrolled frequency. The popular methods to decrease the switch frequency method is the hysteresis modulation (HM), and more advanced method to adjust the hysteresis band can effectively control high frequency switch frequency.

Give reference here as you discuss each method, i.e. "Hysteresis Modulation (HM) [15]…"

✓Highlights strengths and weaknesses of methods.

Although the frequency can be controlled by boundary conditions, it still is variable frequency operation under varied line voltage and load conditions. The varied switched frequency can aggravate the filter design and deteriorates voltage regulation, as well as increases noise and EMI pollutions. Therefore, the SM controller based on PWM is proposed to compare the ramp signal with equivalent signal of SM to generate gate pulse with fixed frequency. Although the fixed frequency can be provided by comparison with ramp signal; the output only can control one switch to chop signal. Therefore, the method to control multiple switches with fixed frequency PSM is proposed to design a SM controller for full-bridge serial-parallel resonant inverter. To consider the SM controller, we can consider the digital control and analog control. If the controller is simple can be accomplished by analog discrete device, it is better without the concern about the sampling and quantification. However, the controller usually is so complicated, that only digital microprocessor can implement it. Therefore, it needs more attention to evaluate the risk to select the best solution in controller design and algorithm discussion.

State clearly how the research will be done and to give a timeline.

6. Multi-level high frequency inverter

State clearly the timeframe and use tenses for time, e.g. "are compared" refers to always future is better, i.e. "will be compared".
State what has already been done.

Use common terms in a standard way, .i.e. need further investigation" or "need to be further investigated".

In order to implement the sinusoidal inverter to output high frequency power, possible high frequency inverter topology need further investigate, which including inverter with sinusoidal PWM modulation, inverter with multi-level PWM modulation, and inverter base on frequency and phase shifted angle modulation. The advantages and disadvantages of them are compared to proposed proper high frequency inverter for different applications.

Conventional or resonant inverter based on sinusoidal PWM modulation

- Pros: more load independent and low cost
- Cons: higher frequency modulation

Conventional or resonant inverter based on multi-level PWM modulation

- Pros: more load independent and lower frequency modulation
- Cons: more components and costly

Conventional or resonant inverter based on frequency or phase shifted angle modulation

- Pros: low cost and low frequency modulation
- Cons: load dependent

To compare them, an appropriate inverter topology need further study according to different power and voltage grade.

Avoid starting paragraphs with phrases starting with "to...", i.e. "An appropriate inverter...and voltage grade to compare them."

7. Soft-Switching and PFC [19, 20]

In addition to the DC/AC inverter, low frequency AC to high frequency AC inverter also need further study, which introduce PFC requirements. To refer to existed PFC and DC/DC converter circuit, the one-stage and two-stage DC/DC converter are proposed to integrate PFC functionality with DC/DC power conversion. However, few of study are to discuss the integration between PFC and high frequency AC inverter. Therefore, the further study can be carried out to discuss the PFC in HFAC inverter, which contains:

Use present perfect tense and plural to describe studies in general, i.e. "Few studies have discussed…"

- Possible topology study on single-stage PFC AC/AC inverter
- Possible unified control enhancement based on existed two-stage PFC AC/AC inverter
- Possible topology study on three-stage high frequency AC inverter including PFC, DC/DC, and DC/AC stages
- Possible unified control enhancement for three-stage topology

✓Lists using same word to start each item in list

The study target is to simplify the circuit structure and save the controller cost without the cut down the waveform quality of HFAC output.

✓States aims clearly, although better that aims are stated at start of section

8. Other possible study

Distinguish between one study and more than one study, i.e. "Other possible studies".

The other items for further study are listed as below, which including cable compensation, automatic identification of high frequency losses, EMI, connection with microgrid, lighting and EV, as well as high frequency AC breaker.

- Others
    - Compensation of cable voltage
    - Automatic identification of high frequency losses
    - EMI
    - Connect with microgrid, lighting and EV
    - High frequency AC breaker and RCD

First word in lists should follow the same style. Numbers or letters are better than bullet points.

"Others" is a vague heading. "Other research foci" is a better option.

Actually, cable compensation is meaningful for HFAC distribution system, because the great transmission losses with terrible sinusoidal waveform. Although the high frequency output in source side can provide the waveform with high quality, the unknown load size, unknown load type both can generate unwanted waveform distortion. Therefore, the compensation of cable voltage is indispensable, especially in long distance transmission like EV and microgrid. In order to compensate the cable voltage, the automatic identification of high frequency losses is premise. The system identification algorithm needs be considered to intelligent distinguish the type and size of power losses.

Distinguish between what will be done and what needs to be done", i.e. "algorithm will be considered..."

Another consideration for HFAD distribution is EMI in transmission. The study and discuss to reduce the EMI need further study. In order to connection with given application, the specific discussion of HFAC is applied to microgrid, lighting and EV. Lastly, the safety is important for HFAC distribution system, the protection is indispensable, such as the breaker, RCD. According the characteristics of IIFAC, the study and discuss of protection device of HFAC need further study.

9. Summary

The summary should focus more on the roadmap and provide a clear timeline.

The HFAC has already been proposed by academy for a few decades, however the application of HFAC still scarce except some low power field. The reason to restrict the application is industry inertia and technical bottleneck. The advantage of HFAC is distinct, which would have a broad application in some occasions with less weight. In the meantime, the technological advances in high frequency cables and magnetic materials, soft switching and resonant converters have significantly lowered technological risks of applying HFAC. It is envisaged that there will be considerable interest in the application of HFAC in emerging markets such as in microgrids and in renewable energy areas, where there are increasing demands for high power conversion efficiency and system flexibility. In proposed PhD research roadmap, we discuss the different research items in power source side of HFAC distribution system, which include power expansion, integration structure topology, PFC, HFAC

✓Restates motivation for study

✓ Include what work has already been done

✓Outlines why the study is important, e.g. interest...in emerging markets..."

inverter topology design, as well as other transmission and EMI issues. Because of the extraordinary of HFAC distribution system, the further research may include but not limited to the proposed roadmaps.

Also state what work has already been done.

10. References

Follow the IEEE guidelines for reference lists for all entries. A reader should have enough information to find all the documents on the reference list.

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