Control of mutiple power inverters for more electronics power systems: A review

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(Invited)

[1]***Abstract*—With the development and utilization of renewable energy, the scaling of microgrid composed of distributed generation systems and energy storing devices, e.g, photovoltaic (PV), wind power, micro gas turbine, fuel cell, are becoming much lager. Research on control of multi-inverter parallel is the focus as the key technique, which can improve the reliability of microgrids. The inverters in the microgrid operate in parallel, which not only facilitates the expansion of the microgrid but also improves the reliability of the operation of the microgrid system in off-grid mode. The key to the parallel operation of the inverter is to achieve even distribution of the load current. In this paper, a comprehensive review on the control strategies of parallel-operated inverters is presented. Also, the detailed analysis, comparison, and discussion on the existing parallel control strategies are investigated.**

***Index Terms*—Parallel inverters, microgrid, distributed power system.**

I. INTRODUCTION

WITH the global economic and social development, the energy crisis and environmental problems have become increasingly serious. The coal, oil and natural gas and other mineral energy are increasingly depleted, forcing people to accelerate the exploration and application of new energy, such as solar energy, wind energy, tidal energy and fuel cell [1-3].

Since the nineties of the last century, various power generation and conversion technologies that make use of renewable energy have been developed rapidly, accompanying the gradual transition of power supply system from centralized power system (CPS) to distributed power supply system (DPS). Compared with CPS, DPS has a series of advantages, such as redundancy, modularization, fault tolerance, reliability, maintainability [4, 5].

Distributed generation is the core of distributed power system, which means that a variety of small-scale energy sources, such as gas turbines and various renewable energy sources, are used at the site of the user or near the site to meet the needs of specific users and support the economic operation of the power grid or to meet these two requirements. These small energy sources include the above-mentioned new energy sources or gas turbines. Distributed generation technology based on new energy sources mainly include solar photovoltaic power generation technology [6, 7], wind power generation technology [8,9] and fuel cell power generation technology [10, 11]. Germany, Denmark, Japan and the United States have a leading position [12]. As a key technology in the development and utilization of new energy, inverter control has become one of the hot spots in power electronics.

On the other hand, it is one of the development direction of power supply technology to realize large capacity and high-reliability power conversion system with multi-module parallel. With the development of electric vehicles and DC microgrids, the demand for high-power charging facilities is becoming more and more urgent. It is a preferred solution for people to increase the power capacity by using the existing power charging modules in parallel, which not only increase system capacity, but also save costs and improve system stability and security [13, 14]. Multiple power modules share the load power in parallel, and the current stress of the main switch devices in each module is small, and the reliability is guaranteed fundamentally. At the same time, each module has smaller capacity and higher power density, so that the volume and weight of the entire power supply will decrease. Standard modularity instead of serialization will also greatly reduce the cost of production and maintenance. The N+X redundant parallel operation (X is redundant module number) obtains the fault-tolerant redundant power at a small cost. No matter national defense or civilian, it is a preferred scheme to achieve the key power supply, high reliability, high power density and high power system. The parallel operation mode of DC power inverter has been widely used in the power supply of the server. However, the inverter is AC output, each module output voltage not only to the same amplitude, and must be the same waveform, the same frequency, phase synchronization, so its parallel operation is much more difficult than the DC converter.

The inverters in the microgrid operate in parallel, which not only facilitates the expansion of the microgrid but also improves the reliability of the operation of the microgrid system in off-grid mode. The key to the parallel operation of the inverter is to achieve even distribution of the load current. For the load current to be distributed evenly between each inverter, it is necessary to maintain the amplitude, phase and frequency of the inverter's output voltage at any moment equality; otherwise it will result in circulating current between the inverters. The circulating current will cause uneven load current distribution, which may cause some inverters to withdraw from microgrid and reduce operation efficiency and reliability of the whole parallel system [15-16].

First, when inverters are operated in parallel, the current flows between the parallel inverters due to the inverters

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connected to the same DC bus and the same load, forming a circulating current [17]. When there are differences between the given parameters of each inverters and the adjustment parameters, the output voltage of no-load inverters will be different.

As the internal resistance of each voltage source inverters is extremely small, partial rectification and active inversion may form a large circulating current between the parallel voltage source inverters, affecting the normal operation of the inverters and reducing the performance of the system, it must suppress the circulating current. At present, there are a lot of literature on control methods of circulating current suppression, mainly adopting the method of coupling inductance [18-19], adopting the method of interphase impedance [20-21], adopting the method of isolating transformer [22-24], adopting the method of improving voltage space vector [25-28] and the method of adding regulator [29-30]. In fact, to avoid circulating current and achieve current sharing are the same problem, to achieve current sharing is to avoid the emergence of circulating current, most of the domestic research from the current sharing point of view to solve the problem. The problem of current sharing is how to distribute the current among all the modules evenly. If the average distribution of the load current among the parallel modules can not be guaranteed, it is bound to increase the output current of some modules and reduce the output currents of other modules, even no output, which will reduce system reliability and security [31]. At present, in the parallel inverters system, the technology of realizing current sharing control include centralized control [32-40], master-slave control [41-48] and decentralized control [49-59], circular chain control [60-61], wireless parallel control [62-79]. The classification map of parallel control strategies are shown in Fig. 1.

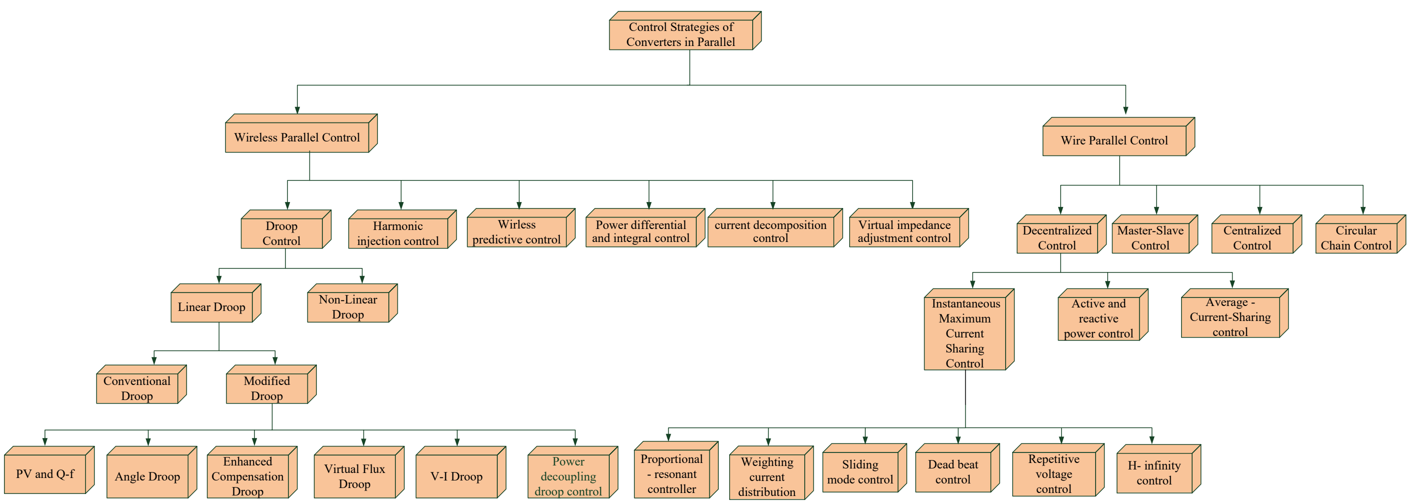

Fig. 1. Classification map of Parallel control strategies.

II. Wire Control Strategies of Inverters in Parallels

In isolated operation (off-grid mode), all distributed micro-sources are supplied to local load in microgrid, which is similar to the operation of multiple groups of uninterruptible power supplies (UPS) in parallel. Multiple inverters in the microgrid operate in parallel, which is beneficial to the large-scale expansion of the microgrid and on the other hand can effectively improve the security and flexibility of the microgrid under islanding. However, the inverter in island operation is in voltage control mode and the inverter parallel system is equivalent to multiple controllable voltage sources operating in parallel. Taking into account that the inverter does not have similar external characteristics of synchronous generators, the output voltage amplitude, frequency and phase angle differences will result in circulating current between the inverter, and even led to individual inverter trip-out from the micro-grid, causing micro-grid islanding bus support voltage and frequency of rapid fluctuations, which is not conducive to the inverter parallel system efficient and stable operation [67-68]. Therefore, the key to the parallel operation of the inverter in island mode lies in how to distribute the load power rationally, and realize the accurate distribution of the load current according to the rated capacity ratio of each inverter to suppress the circulating current between the inverters.

A. Centralized Control

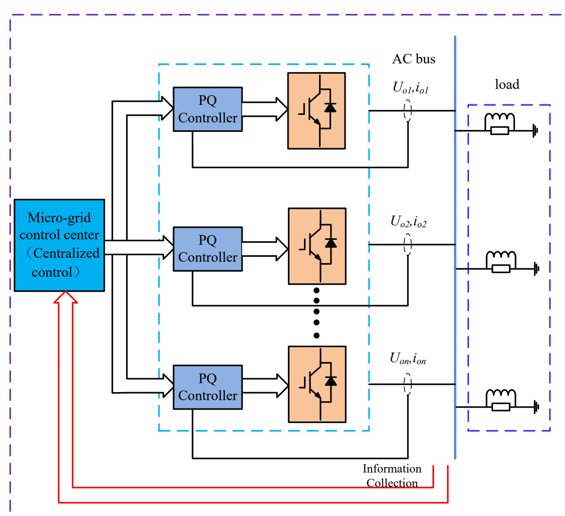

Fig. 2. Parallel structure of inverter based on centralized control mode.

At present, the control technologies for parallel operation of inverters can be roughly divided into two types: wire control and wireless control. Structure block diagram of parallel inverter using centralized control mode, as shown in Fig. 2. From Fig. 2, it can be seen that the centralized control features are: microgrid multi-inverter parallel system reference power signal is mainly provided by the micro-grid control center, the reference power signal subtracting from the actual active and reactive power detected by the inverter getting current deviation (PQ control), their difference as the output voltage command compensation, in order to achieve the proportion of the load current distribution. The centralized control mode of inverter is easy to realize engineering application. However, once the control center of microgrid fails or the line breaks, the whole parallel control system will collapse, so the reliability is low.

B. *Master-slave control*

In order to overcome the problem of low reliability of the centralized controller in centralized control mode, a possible solution based master-slave control can be used. The principle diagram of the master-slave inverter in parallel inverter is shown in Fig. 3. Among them, the inverter of the master control unit adopts constant voltage and frequency control (V/f control) to provide voltage and frequency reference to other control units and the inverter of the slave control unit adopts PQ controller. However, once the microgrid is switched to grid-connected operation, the inverter, which is the master control unit, needs to be quickly converted from the V / f control mode to the PQ control mode, which requires that the master controller be capable of operating between two-control modes quick switch. Once the master control unit fails to switch the working mode, the entire parallel control system will be difficult to maintain operation stably.

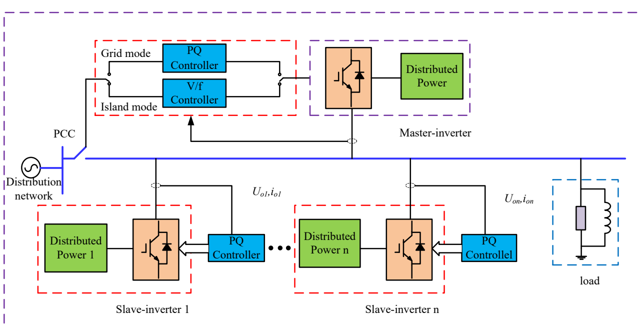

Fig. 3. Parallel system structure of inverter based on master-slave control.

C. *Decentralized* control

In order to overcome the problem of low reliability of the centralized control and the master-salve control, the decentralized control theory can be used. The principle of decentralized control mode is that the status of each inverter in the parallel system is equal and there is no fixed master or slave. When one of the inverters exits the parallel system due to fault, the operation of the remaining parallel inverters is not affected. Decentralized control can be divided into three types: instantaneous current sharing control and active power reactive power sharing control.

The instantaneous maximum current sharing control block diagram of parallel inverters is shown in Fig. 4. There is a synchronous bus and a current bus in the system. The synchronous bus is used to realize the phase synchronization between parallel inverters. Each module obtains the maximum current from the current bus as the current reference for the circulating current regulator. The output of the circulating current regulator is superimposed on the output of the current regulator so that the load current is shared equally.

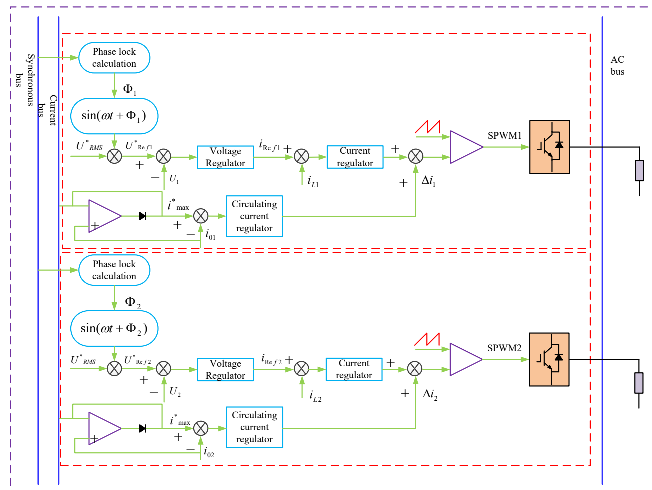

Fig. 4. Instantaneous maximum current sharing control for parallel inverters.

The decentralized control of parallel inverters based on instantaneous current sharing can obtain good steady and dynamic current sharing performance. However, as the parallel system expands, the distribution distance between parallel inverters will increase, leading to the current bus transmission of analog signals are more susceptible to interference, resulting in lower reliability of the overall parallel inverter system, which will reduce the reliability of the entire parallel inverter system. At the same time, with the increasing number and capacity of parallel system units, interconnection lines between inverters will become more and more complex, and the reliability of inverter parallel systems will become increasingly worse.

The schematic block diagram of a parallel inverter based on active power and reactive power control is shown in Fig. 5. It can be seen from the Fig. that both active and reactive power flow control use CAN bus to transmit active and reactive power among UPSs in the parallel system and calculate the average power as the reference to control the output voltage amplitude and phase angle, so that the load current evenly distributed between the stations, because the CAN bus is transmitted digital signal, which is not subject to interference, thus greatly improving the reliability of the system.

The parallel system based on active power and reactive power sharing current control can effectively suppress the AC current and achieve the power sharing, but cannot suppress the DC current automatically. When the inverter adopts sinusoidal pulse width modulation technology, due to inconsistent saturation voltage drop across the upper and lower switching tubes of the same bridge arm, asymmetric drive pulse distribution, and zero drift of the operational amplifier in the control circuit, the inverter output voltage may have a direct current component, which lead to the DC circulating current between the parallel inverter.

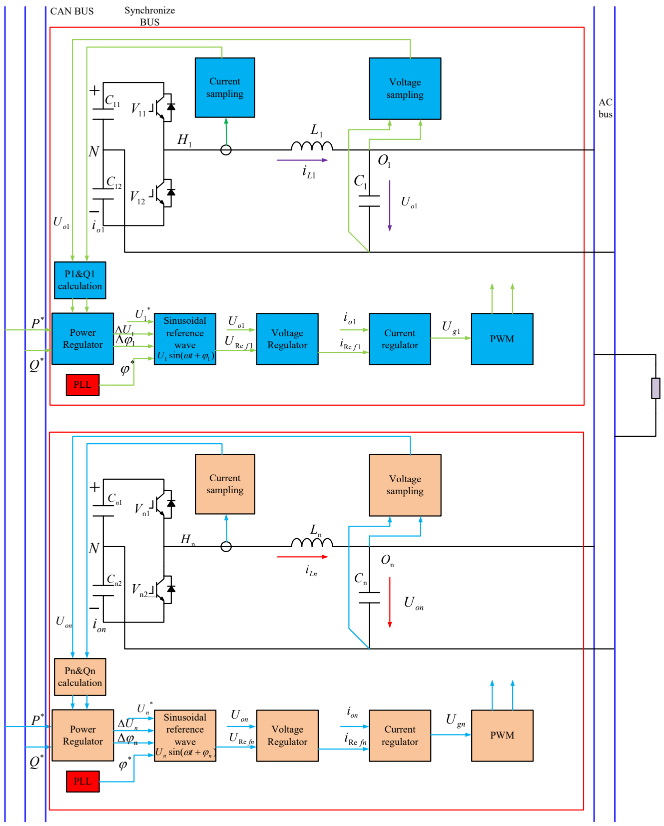

Fig. 5. Active and reactive power control of parallel inverters.

In [59], the principle of DC circulating current suppression in parallel system of inverter is that the DC current is detected by using current LEM and DC circulating current is suppressed by adjusting the output DC component of each inverter. In addition, the method can only control the output DC voltage components of the parallel inverter module to be equal, and can not eliminate the DC component in the output voltage of a single inverter. In this way, the DC current generated by the DC component of the voltage will flow through the load, which will be harmful to the load. At the same time, when the scheme is used to adjust the DC circulation of the parallel system in the multi module parallel connection, and it is easy to make the fault of the parallel system caused by the error regulation of individual modules.

D. Circular chain control

The principle diagram of the circular chain control (3C) inverter in parallel inverter is shown in Fig. 6. In the Fig., the current reference signal of each module is taken from the previous module, the current reference of the first module is taken from the last module, and all the current reference signals form a ring. i_{Lj_r} is the inductor current reference signal of the j th module, i_{Lj} is the inductor current signal of the j th module. The output current and voltage of each module are respectively regulated by the current inner loop and the voltage outer loop, and the response speed of current inner loop is fast. Each module shares the same voltage reference signal and their output voltages are very close.

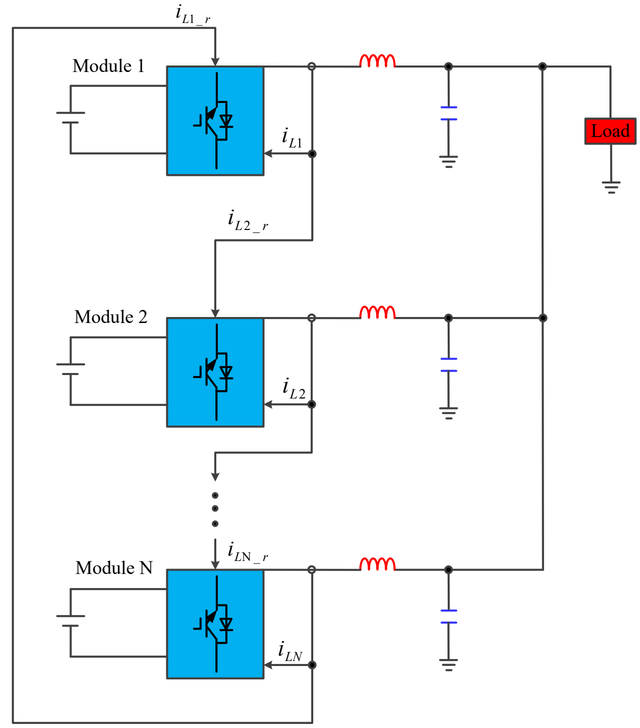

Fig. 6. Parallel system structure of inverter based on circular chain control.

Theoretical analysis shows that the characteristics of the voltage transfer function of the parallel system voltage vary with the number of parallel modules and the load. In [60-61], it adopts the output voltage outer loop based on H^{∞} robust controller, which improves the robustness of the parallel system and reduces the interaction between parallel modules. By performing bidirectional communication between modules in the parallel system, which improve the reliability of the 3C parallel system and realize the hot swap function.

The disadvantage of 3C is that the mutual influence is large between the modules of the parallel system, and it is complicated to design the output voltage outer loop, and many measures are taken to improve the system reliability.

III. Wireless Control Strategies of Intervers in Parallels

A. Voltage-Frequency Droop Control

In order to reduce the control signal line between the inverters, literature [62-69] proposed wireless control strategy for parallel; the basic principle is shown in Fig. 7. Compared with centralized control and master-slave control, wireless control has the advantages of less connecting lines, strong anti-interference ability, low system redundancy, high reliability and easy expansion. The method is based on the control concepts of "*equivalence*" and "*plug and play*" in power electronics technology. According to the control objectives of the multi-inverter parallel system, the method uses the external characteristics of the traditional synchronous generator as the distributed power source of the microgrid control mode, without control bus and communication bus. Dynamically distribute load power to all distributed power sources. Each inverter adopts droop control to participate in the voltage and frequency adjustment of the microgrid to ensure the balance between supply and demand of the microgrid. When the load of the microgrid changes, the inverters share the load power proportionally according to the droop coefficient, that is, by adjusting the output voltage amplitude and frequency of the inverter, the multi-inverter parallel system reaches a new stable operating point to achieve reasonable distribution of output power.

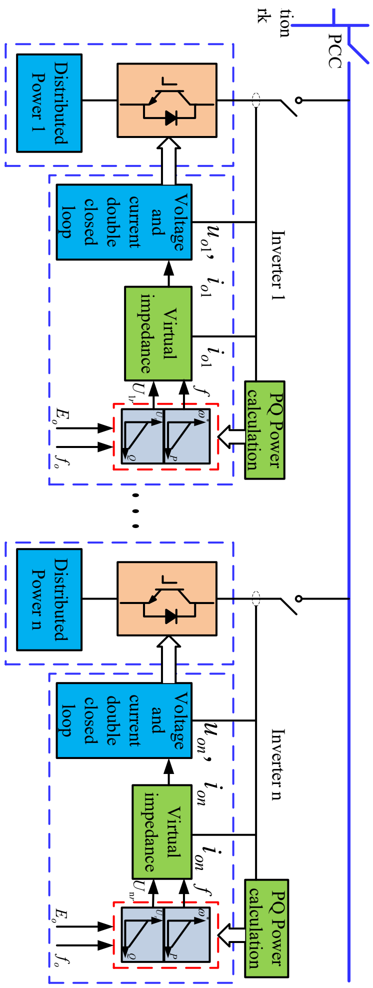

Fig. 7. Parallel connection system structure of wireless inverter based on droop control.

B. Parallel control based on current decomposition

In [70], it proposed a wireless parallel method based on current decomposition, so that the harmonic power is equally divided. The control block diagram is shown in Fig. 8. The average of the output fundamental active and reactive power is still controlled by the conventional PQ droop, but it added the calculation of the output harmonics current, the output of the voltage loop PI regulator is combined with the harmonic component of the load current to synthesize the reference of the current loop, and finally the corresponding PWM signal is output through the PI regulator. The advantage of this method is that the output harmonic current is evenly divided, and the power sharing effect is better when the nonlinear load is used, and the disadvantage is that the calculation is complicated.

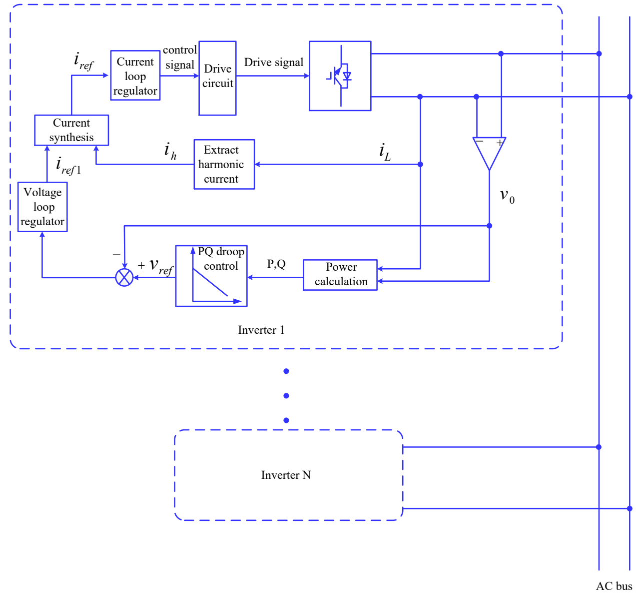

Fig. 8. Parallel system structure of wireless inverter based on current decomposition.

C. Parallel control based on power differential and integral links

In [71], an additional transient drooping part is added to the usual power droop control equation. The control block diagram is shown in Fig. 9. The transient drooping part mainly uses power integral and differential, and at the same time, the phase angle drooping of the output voltage is used to replace the commonly used frequency drooping, which not only ensures the steady state performance of the system, but also improves the dynamic performance of the system. The parallel control equation is:

$$\begin{cases} \phi = -m\int_{-\infty}^{t} P d\tau - m_p P - m_d \dfrac{dP}{dt} \\ E = E^* - nQ - n_d \dfrac{dQ}{dt} \end{cases} \tag{1}$$

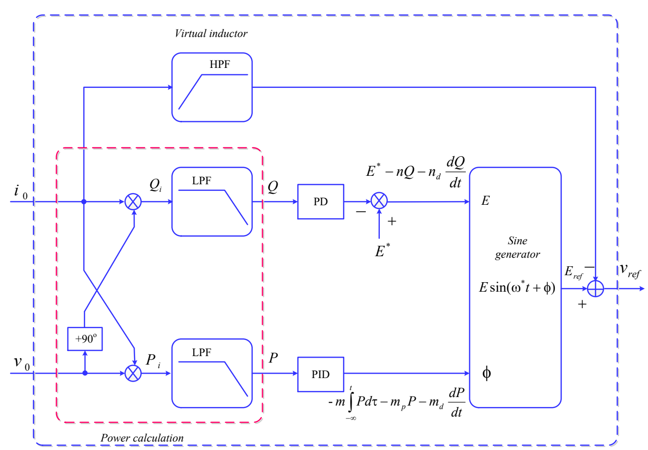

Fig. 9. wireless control strategy based on power differential and integral links.

D. Harmonic injection control strategy

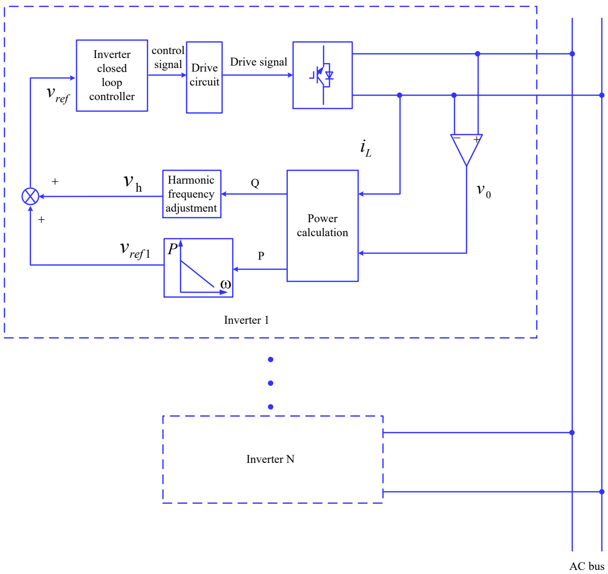

Fig. 10. Wireless control strategy based on harmonic injection.

Injecting a harmonic with a small amplitude (about 1%-2% of the amplitude of the fundamental voltage) into the reference voltage, the frequency of the harmonic is adjusted by the output power of the inverter, the output voltage amplitude adjustment of the inverter adopts the harmonic active power droop to realize the average of the reactive power and the harmonic power of the inverter parallel system [72-73]. The method can reduce the influence of lead resistance on the parallel system, but the harmonic component of the output voltage waveform becomes larger and the THD is larger. The parallel control block diagram is shown in Fig. 10.

D. Virtual impedance adjustment control strategy

The virtual impedance control method is shown in Fig. 11. In the closed-loop control of the inverter, adaptive virtual impedance is introduced to adjust the equivalent output impedance of the inverter to achieve the average of reactive power, at the same time, the frequency of the reference voltage is adjusted by the drooping control of the AC component of the active power. The virtual impedance can be used to conveniently adjust the output impedance properties in different frequency ranges to obtain a more accurate output current sharing [73-79]. In addition, the method can avoid the attenuation of the output voltage of the inverter and improve the output voltage regulation rate. The disadvantage of the method is that the calculation is complicated.

TABLE I
ADVANTAGES AND DISADVANTAGES OF CONTROL STRATEGY OF PARALLEL INVERTERS

Control strategy	Advantage	Disadvantage
Centralized control [32-40]	Simple control mechanism, Load sharing during steady state and transient, voltage regulation	Requires communication among inverters, Low expandability, Slow response, interference to load at times of maintenance, Low reliability
Master slave control [41-48]	Good load sharing in steady state, system is immune to failure due to slave inverters, simple to regain the output voltage at times of disturbance , current accretion and distribution control logic hold good	Requires high bandwidth for communication, Prone to system failure due to the master failure, Low redundancy
Decentralized control [49-59]	Constant frequency and fundamental power sharing achieved, Accurate power sharing with symmetrical inverters	Requires communication, Demands individual control of each inverter, Tracking mechanism error, inaccurate power share with different power rating, Low modularity
Circular chain control [60-61]	Response fast, Improves the robustness of the parallel system and reduces the interaction between parallel modules, Improve the reliability of the 3C parallel system and realize the hot swap function	The mutual influence is large between the modules of the parallel system, and it is complicated to design the output voltage outer loop , and many measures are taken to improve the system reliability
Wireless control [62-79]	Avoids communication, good power sharing, different power sharing, high reliability, expandability and modularity, Low band width is enough	Power sharing attained at an expense of voltage regulation, Slow response

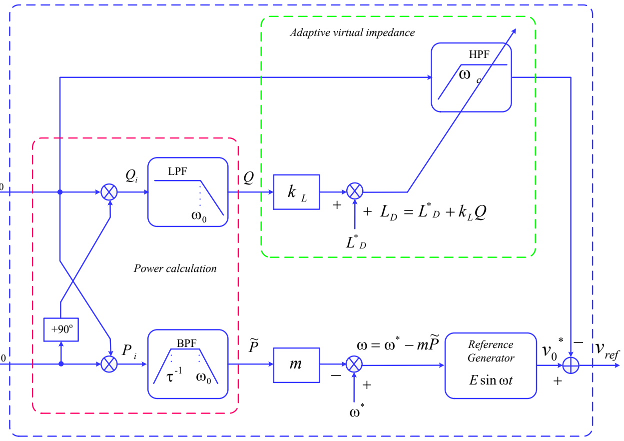

Fig. 11. wireless control strategy based on virtual impedance adjustment.

IV. Comparative Analysis

The control strategies were selected based on criteria's like control signal communication and the control loop in the parallel inverter system. The centralized control , master-slave control and decentralized control, circular chain control are communication based control strategies and the droop control is a communication less control that does not necessitates for a reliable communication. The Table I depicts the merits and demerits of the different control strategies.

V. Conclusion

With the development and utilization of renewable energy, the scaling of microgrid composed of distributed generation systems and energy storing devices, e.g. photovoltaics (PV), wind power, micro gas turbine, fuel cell, and so forth, are becoming much larger. Whether the micro-grid works in the grid-connected mode or the off-grid mode, it is necessary to control the converter. It is important for enduring the reliable operation of the micro-grid with the multi-converter parallel control technology, which is becoming the hotspot of current research. In this paper, a comprehensive review on the control strategies of parallel-operated inverters is presented. Additionally, detailed analysis, comparison, and discussion on the existing parallel strategies are investigated. It is expected that this review will be a helpful reference on parallel of inverters for the researchers, engineers, manufactures and users concerning control strategies of parallel-operated inverters.

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