Research on the Control Method of UPS Inverter Circuit Considering Additional Filtering Branch

Guofu Liu1, Ximu Liu2,∗ and Weiwei Wang3
1Liaoning Electric Power Energy Development Group Co., Ltd., Shenyang, China
2School of Electrical Engineering, Northeast Electric Power University, Jilin, China
3State Grid Jinzhou Electric Power Supply Company, State Grid Liaoning Electric Power Supply Co., Ltd., Jinzhou, China

∗Corresponding author email: 1142101056@ncepu.edu.cn

Abstract. Improving the electric power quality of the Uninterruptible Power Supply (UPS) is an important part of ensuring the reliability of the power system. In order to optimize the output voltage waveform of the UPS, a filtering branch can be added to the existing UPS inverter circuit. This paper studies the circuit control problem after adding the RLC filter branch in the UPS inverter circuit. Through the analysis of the inverter circuit directly considering the added filtering branch, the system state function of the circuit is constructed. A double closed-loop PI control strategy is designed to control the inverter circuit, and the effectiveness of the method is verified by simulation. Using the method in this paper, the output of the inverter circuit with the added filter branch can reach a stable state quickly. The research conclusions of this paper are helpful to improve the output power quality of UPS.

1. Introduction
With the development of power electronics technology, the requirements for power quality and safety are increasingly improved. Uninterruptible Power Supply (UPS) is capable of providing stable, continuous and uninterrupted electric power [1]-[3]. Owing to the rapid development of advanced technologies such as information technology and computer technology, the number of electrical equipment in the power grid is increased, the requirement of reliability of power supply systems is becoming higher and higher. The interruption of electric power will cause data loss and even damage the hardware, resulting in system paralysis and major losses. UPS is one of the best ways to improve the reliability of the power supply [4]-[6].

As a power modulator between the DC input and the AC load, the voltage-type inverter can convert DC power to AC power and provide the ideal output voltage and frequency for the output. The voltage type inverter has a fast response and precise control, and is widely used in industrial fields. The control strategy of inverter is focused in the studies [7]. A well-designed inverter should have the characteristics of fast convergence speed, small error and strong robustness [8].

The voltage waveform output by the inverter often contains harmonics [9]. In order to improve the power quality and reduce the harmonics of the output voltage, a filtering branch can be added to the existing UPS inverter circuit in engineering practice [10]. At this time, if the added filter circuit element is directly integrated into the existing filter element and the circuit is analyzed by using lumped parameters, the actual situation of the circuit may not be fully taken into account. Until now, the problem of controlling the inverter circuit after adding the filter branch is still a lack of study [11-13].
This article has directly studied the inverter circuit containing the added filter branch. Firstly, the way to connect the online UPS inverter circuit to the power system is analyzed. On this basis, a circuit model is established and a coefficient state matrix and an input matrix are constructed. Finally, double closed-loop PI control strategy is used to control the inverter system.

2. The Connection of UPS Inverter Circuit and Power System
The structural framework of the online UPS power supply is shown in Figure 1. When the main power is normally supplied, the AC power is converted into direct current by the AC-DC converter. While the battery is charging, the power is converted into alternating current by the DC-AC inverter to provide power to the load. When the main power is interrupted, the DC power stored in the battery is immediately converted to AC power by the DC-AC inverter to provide power to the load. Regardless of whether the main power is normal or interrupted when supplying power, the AC power used by the load is obtained through the DC-AC inverter conversion. The inverter is always in a normal working state during this process. In this way, the circuit can solve the problems of the voltage fluctuation and interference generated from the power grid. Therefore, the UPS power supply can achieve the purpose of voltage stabilization, frequency stabilization and the interference can be eliminated. If the UPS inverter fails or is repaired, the circuit can be immediately switched to the bypass branch to provide power to the load directly in order to ensure uninterrupted power supply.

![Figure 1. Frame diagram of online UPS power supply with bypass branch.](image)

The mode of the UPS inverter circuit is shown in Figure 2. The input circuit sends the DC voltage to the inverter circuit and then converted into AC voltage output by the inverter circuit. The function of the control circuit is to trigger and shut down the power electronic device in the inverter circuit. Adjust the turn-on and turn-off time of the power electronic components according to the output voltage frequency, amplitude and phase detection results. The function of the protection circuit is to cut off the inverter circuit in time when the inverter system is failed.

![Figure 2. Typical UPS inverter circuit and the corresponding control circuit.](image)

3. Analysis of Inverter Circuit with Additional Filtering Branch
The structure of the inverter circuit is shown in Figure 3. The circuit includes thyristors $S_1$ and $S_2$ connected in series and thyristors $S_3$ and $S_4$ connected in series. Among them, thyristors $S_1$ and $S_3$ are connected in parallel to node 1, and thyristors $S_2$ and thyristor $S_4$ are connected in parallel to node 2. A diode is connected in parallel across each thyristor.
The filter circuit structure includes a series resistor $R_1$, an inductor $L_1$ and a parallel capacitor $C_1$. The resistor $R_2$, the inductor $L_2$ and the capacitor $C_2$ are filtering branches added in order to improve the output power quality. Among them, the resistor $R_1$ and the inductor $L_1$, the resistor $R_2$ and the inductor $L_2$ are connected to the node 3 with the capacitor $C_1$. The capacitor $C_2$ is connected to the resistor $R_2$ and the inductor $L_2$ to the node 4. The load of this circuit is $R_{LD}$. $V_{DC}$ is the DC input voltage and $V_{C2}$ is the output voltage.

![Figure 3. Schematic diagram of inverter circuit topology considering additional filter branch.](image)

In the next, the circuit structure in Figure 3 is analyzed and the relationship between the variables is determined. The state space expression of the system is

$$
\dot{x} = Ax + Bu
$$

where $A$ is a state matrix and $B$ is an input matrix. Take the state vectors

$$
x^T = [i_{c1}, v_{c1}, i_2, v_{c2}]
$$

The relationship between input and output voltage is

$$
V_o = V_{dc} \cdot u
$$

Using Kirchhoff’s voltage law (KVL) and current law (KCL), there is

$$
\begin{align*}
    v_0 &= R_1 i_i + L_1 \frac{di_i}{dt} + v_{c1} \\
    i_i &= i_{c1} + i_2 \\
    i_2 &= i_{c2} + \frac{v_{c2}}{R_L} \\
    v_{c1} &= R_2 i_2 + L_2 \frac{di_2}{dt} + v_{c2}
\end{align*}
$$

From the above equations, there is
\[
\begin{align*}
\frac{d^2 v_{C2}}{dt^2} & = \frac{1}{L_2 C_2} \left[ v_{C1} - R_2 i_{C2} - \frac{L_2 i_{C2}}{R_2 C_2} - \left( \frac{R_3}{R_L} + 1 \right) v_{C2} \right] \\
\frac{di_{C2}}{dt} & = \frac{1}{L_2} v_{C1} - \frac{R_2}{L_2} \left( \frac{R_2}{R_L} + \frac{1}{R_L C_2} \right) i_{C2} - \frac{R_2 + R_L}{L_2 R_L} v_{C2} \\
\frac{dv_{C1}}{dt} & = \frac{v_0 - R_1 i_{C1}}{L_1} + \left( \frac{R_1}{L_1} + \frac{R_2}{L_2} \right) i_2 - \frac{1}{L_1} v_{C1} + \frac{1}{L_2} v_{C2}
\end{align*}
\] (5)

The final coefficient matrix and input matrix are
\[
A = \begin{bmatrix}
-\frac{R_1}{L_1} & -\left( \frac{1}{L_1} + \frac{1}{L_2} \right) & -\frac{R_1}{L_2} & \frac{1}{L_2} \\
\frac{1}{C_1} & 0 & 0 & 0 \\
0 & 1 & -\frac{R_2}{L_2} & -\frac{1}{L_2} \\
0 & 0 & \frac{1}{C_2} & -\frac{1}{R_L C_2}
\end{bmatrix}, \quad B = \begin{bmatrix}
V_{DC} \\
0 \\
0 \\
0
\end{bmatrix}
\] (6)

4. Control Method of Inverter Circuit

Digital control of sine inverter has been a topic of great concern. Based on PID control method, this paper adopts double closed-loop feedback control to control the inverter, as shown in Figure 4. This method does not rely too much on system parameters. The reliability of this method is high. The robustness and static and dynamic characteristics can be guaranteed as well.

![Figure 4. Double closed-loop inverter control system of UPS.](image)

The basic principle of voltage control is to convert the inverter output sinusoidal signal into a DC feedback signal \(V_I\) (effective value signal) through rectification, and compare it with the effective value reference signal \(V_{ref}\). After the PI error is amplified to obtain \(V_{ref}\), the value of \(V_{ref}\) is multiplied by the reference sine wave and sent to the PWM modulator. Finally, the inverter switch is controlled. Thereby, there is no static error tracking of the fundamental wave. This kind of voltage control has a very good effect on linear loads. The steady-state error under heavy loads can be effectively reduced.

A circuit simulation model was built in Matlab/Simulink software to verify the method from this paper. The simulation program is started from the moment when the output voltage is 0V. The voltage output results are shown in Figure 5. Simulation results show that after 8 periods, the output voltage reached a steady state. The method in this paper can make the UPS inverter output a sinusoidal voltage waveform with reliable power quality and response rate.
5. Conclusion
This paper studies the control problem after adding a filter branch to the existing UPS inverter circuit. By analyzing the inverter circuit directly considering the external filtering branch, the construction of the coefficient state matrix and the input matrix is obtained. A double closed-loop PI control strategy is designed to control the inverter circuit. Simulation results show that the output of the inverter circuit can reach a stable state within 8 periods, and the output power quality and response speed of the UPS are effectively guaranteed.

References
[1] Bidram A Davoudi A 2012 Hierarchical structure of microgrids control system IEEE Transactions on Smart Grid vol 3 no 4 pp 1963-1976
[2] Yao W Chen M and Matas J 2011 Design and analysis of the droop control method for parallel inverters considering the impact of the complex impedance on the power sharing IEEE Transactions on Industrial Electronics vol 58 no 2 pp 576-588
[3] Cortes P Ortiz G Yuz J I 2009 Model predictive control of an inverter with output LC filter for UPS applications IEEE Transactions on Industrial Electronics vol 56 no 6 pp 1875-1883
[4] Pal A and Basu K 2020 A single-stage soft-switched isolated three-phase DC-AC converter with three-phase unfolder IEEE Transactions on Power Electronics vol 35 no 4 pp 3601-3615
[5] Chang J and Xiao L 2020 Observer-based load current sensorless control strategy of inverter circuit in three-phase UPS Journal of Power Electronics vol 20 no 1 pp 142-151
[6] Issa W Sharkh S and Abusara M 2019 Hybrid generators-based AC microgrid performance assessment in island mode IET Power Electronics vol 12 no 8 pp 1973-1980
[7] Mahmood H Michaelson D Jiang J 2015 Accurate reactive power sharing in an islanded microgrid using adaptive virtual impedances IEEE Transactions on Power Electronics vol 30 no 3 pp 1605-1617
[8] Zhong Q 2013 Robust droop controller for accurate proportional load sharing among inverters operated in parallel IEEE Transactions on Industrial Electronics vol 60 no 4 pp 1281-1290
[9] Lin Q Cai F and Wang W 2019 A high-performance online uninterruptible power supply (UPS) system based on multitask decomposition IEEE Transactions on Industry Applications vol 55 no 6 pp 7575-7585
[10] Wei B Marzabal A and Perez J 2019 Overload and short-circuit protection strategy for voltage source inverter-based UPS IEEE Transactions on Power Electronics vol 34 no 11 pp 11371-11382
[11] Chang, J., & Xiao, L. (2020). Observer-based load current sensorless control strategy of inverter circuit in three-phase UPS. Journal of Power Electronics, 20(1), 142-151.
[12] Heydari-Doostabad, H., & Ghazi, R. (2019). A new approach to design an observer for load
current of UPS based on Fourier series theory in model predictive control system. *International Journal of Electrical Power & Energy Systems*, 104, 898-909.

[13] Monteiro, V., Catalao, J., Sousa, T., Pinto, J., Mezaroba, M., & Afonso, J. (2020). Improved voltage control for the electric vehicle operation in V2H mode as an off-line UPS in the Context of smart homes. *EAI Endorsed Transactions on Energy Web*, 7(25).