Smartphone Fast Charger Analysis Based on RLC Circuit Transient Process

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Abstract. In today's era, the widespread adoption of mobile terminals, particularly smartphones, has been facilitated by the rapid advancements in information and communication technology. However, a notable drawback of smartphones is their high-power consumption, necessitating faster charging solutions to enhance user convenience. This paper focuses on the RLC circuit of fast chargers. Initially, it introduces the fundamental principles and associated protocols of fast charging technology, elucidating the operation of integrated circuits within fast chargers and highlighting the advantages of fast charging compared to conventional slow charging methods. Moreover, the paper conducts an in-depth analysis of the transient processes within the pivotal series RLC circuit in fast chargers, encompassing zero-input responses and sinusoidal AC excitation responses. The transient processes are categorized into overdamped, critically damped, or underdamped states based on circuit element parameters, with initial conditions and power supply phase determining whether the circuit transitions directly into a steady-state process when stimulated by sinusoidal AC. This research contributes to a deeper understanding of the RLC circuit within smartphone fast chargers and serves as a valuable reference for advancing the development of fast charging solutions.

Keywords: Fast Charging Technology; RLC Circuit; Smartphone Chargers; Power Consumption.

1. Introduction

Today, mobile terminals represented by smartphones have been widely used with the rapid development of information and communication technology. High power consumption is one of the characteristics of smartphones [1]. So, smartphones require faster charging speed to provide users with a convenient experience. The traditional mobile phone charger whose output is 5V1A has low output power and cannot meet the requirements of users to shorten the charging time. Therefore, it is necessary to study the fast charger.

The RLC circuit of fast charger is the focus of this paper. Firstly, the basic principle and related protocols of fast charging technology are introduced. The working process of the integrated circuit in the fast charger and the advantages of fast charging over slow charging are also explained. Furthermore, the transient processes of the most critical series RLC circuit in the fast charger are analyzed, including zero-input response and sinusoidal AC excitation response. The transient process can be divided into overdamped state, critically damped state and underdamped state based on the element parameters in the circuit. The initial conditions of the circuit and the initial phase of the power supply determine whether the circuit directly enters the steady-state process after being excited by sinusoidal AC. At the end of the paper, the challenges and future development trends of fast charging technology are put forward, and some conclusions are given. The research of the paper will contribute to the understanding of the RLC circuit in the smartphone fast charger and provide reference for the further development of the fast charger.

2. The principle of smartphone fast charger

2.1. Fast charging technology of smartphone

There are two ways to improve the charging power of smartphone fast charger according to the power expression $P = UI$. One is to increase the charging voltage, and the other is to increase the charging current. The charging power is increased in these two ways, so that the charging time of

smartphones is shortened. Smartphone charging consists of four links: charger, charging cable, power management chip in the phone, and battery. First of all, the charger is responsible for converting high-voltage AC into low-voltage DC. Second, the charging cable is responsible for transmitting DC to the phone. The power management chip is then responsible for converting the voltage output by the charger into a voltage acceptable to the battery. Finally, the battery receives DC to store electrical energy. To charge the phone efficiently, the above four links need to comply with the specific fast charging protocol at the same time. Fast charging protocols include Qualcomm's Quick Charge series protocols, Huawei's Super Charge and Fast Charge protocols, OPPO's VOOC series protocols, vivo's FlashCharge protocols, MediaTek's Pump Express Plus protocols and so on. These protocols increase the charging voltage from 5V to 9V, 12V or even 20V, or increase the charging current from 1A to 2A, 4A, etc. [2]. The increase of charging voltage mainly depends on increasing the output voltage of the charger, which is determined by the integrated circuit in the charger.

2.2. The working process of the integrated circuit in fast charger

The integrated circuit in fast charger is shown in Figure 1. The circuit is mainly composed of AC rectifier bridge, RCD clamp circuit, flyback transformer, power switch Q1, continuous current diode, filter circuit, output load and optocoupler feedback adjustment circuit [3].

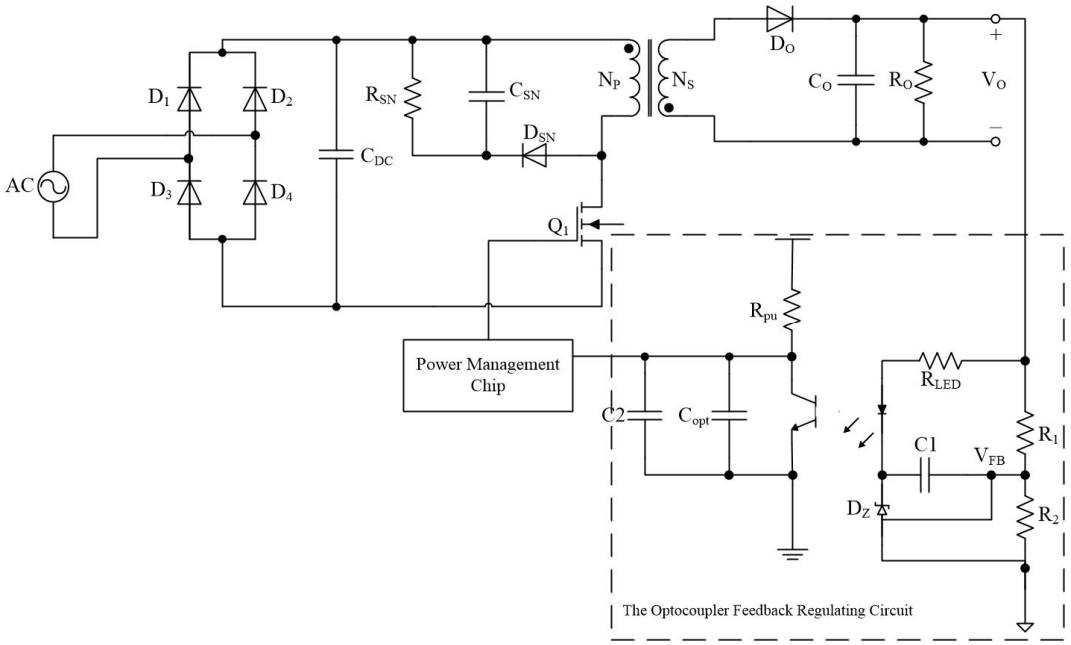


Fig. 1 The integrated circuit in fast charger [3]

The rectification for AC voltage is completed by the rectifier bridge, which is composed of diodes D_1, D_2, D_3 and D_4. Then the AC-DC transform is realized by the rectification and the filtering performed by the filter capacitor C_{DC}. The RCD clamp circuit is composed of R_{SN}, C_{SN} and D_{SN}, which protects the power switch Q_1, absorbs the energy of leakage inductance, avoid Q_1 damage caused by high voltage at the moment of the switch, and ensure the safe and reliable operation of the flyback transformer. The power switch Q_1 controls the on and off of the primary circuit and adjusts the stored energy. The function of continuous current diode D_O is unidirectional conduction. When Q_1 is turned on, the secondary side of the transformer is blocked, and energy is stored. When Q_1 is turned off, the secondary side of the transformer is turned on, and energy is released [4]. The filter circuit is composed of R_O and C_O, which is used to reduce ripple. The optocoupler feedback regulating circuit samples the output voltage by sampling resistors R_1 and R_2. The output voltage is compared with the reference voltage of the three-terminal voltage regulator D_Z to form an error voltage, which changes the current flowing through the optocoupler. Then the change is fed back to the input pin of the power management chip. The power management chip adjusts the power tube Q_1 according to the change of current [5].

2.3. Advantages of fast charging over slow charging

Fast charging has obvious advantages over slow charging. Take the USB PD protocol, which is the representative protocol of fast charging technology, as an example, the advantages of fast charging include:

a) Faster charging speed. Compared with slow charging technology, fast charging supports higher voltage and current and provides higher power output, thus achieving faster charging speed.

b) Flexible power transmission. The fast-changing technology can dynamically adjust the charging power according to the needs of the equipment, which means that the fast charger can provide appropriate power output through negotiation with the equipment to avoid overcharging and overheating [6].

c) Multiple transmission functions. Fast charging technology can support data and video transmission in addition to power transmission. By using a Type-C connector that supports USB PD, users can transfer data or connect external display devices while charging. In this way, multiple needs of users can be met simultaneously through a single interface.

d) good compatibility. USB PD fast charging technology is a general standard, which is supported by many devices and chargers. Users can use the same USB PD charger to charge multiple devices, which makes USB PD a convenient and economical charging solution [7].

3. The transient process of series RLC circuit

In the integrated circuit of fast charger, series RLC circuit plays an important role. The transient process of series RLC circuits is analyzed in this section.

3.1. The zero-input response of series RLC circuit

Firstly, the zero-input response of the series RLC circuit is considered, which is the response of the circuit when there is no external excitation. The zero-input response circuit of the series RLC circuit is shown in Figure 2.

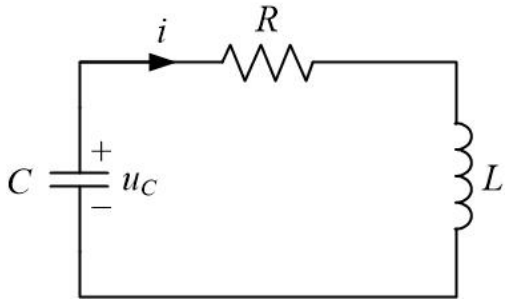


Fig. 2 The zero-input response circuit of the series RLC circuit (Photo/Picture credit: Original)

The KVL equation of the circuit is

$$u_R + u_L + u_C = 0 \tag{1}$$

where

$$u_R = Ri \tag{2}$$

$$u_L = L\frac{di}{dt} \tag{3}$$

$$i = C\frac{du_C}{dt} \tag{4}$$

By substituting equations (2), (3), and (4) into equation (1), the second order differential equation is obtained as follows:

$$LC\frac{d^2u_C}{dt^2} + RC\frac{du_C}{dt} + u_C = 0 \tag{5}$$

The characteristic equation of equation (5) is

$$LC\lambda^2 + RC\lambda + 1 = 0 \tag{6}$$

The characteristic root of equation (6) is

$$\lambda_{1,2} = -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}} \tag{7}$$

Let $\delta = R/(2L)$, $\omega_0 = \sqrt{1/(LC)}$, and $\alpha^2 = \omega_0^2 - \delta^2$, then.

$$\lambda_{1,2} = -\delta \pm \sqrt{\delta^2 - \omega_0^2} \tag{8}$$

When $\delta^2 > \omega_0^2$, λ_1 and λ_2 are two unequal real roots. In this case, the circuit is overdamped, and the general solution of equation (5) is.

$$u_C = A_1 e^{\lambda_1 t} + A_2 e^{\lambda_2 t} \tag{9}$$

When $\delta^2 = \omega_0^2$, λ_1 and λ_2 are two equal real roots. In this case, the circuit is in a critically damped state, and the general solution of equation (5) is

$$u_C = A_3 e^{-\delta t} + A_4 t e^{-\delta t} \tag{10}$$

When $\delta^2 < \omega_0^2$, λ_1 and λ_2 are a pair of conjugate complex roots, $\lambda_{1,2} = -\delta \pm j\alpha$. In this case, the circuit is underdamped, and the general solution of equation (5) is.

$$u_C = e^{-\delta t}(A_5 \cos \alpha t + A_6 \sin \alpha t) \tag{11}$$

The coefficients A_1, A_2, A_3, A_4, A_5, and A_6 in equations (9), (10), and (11) are determined by $u_C(0)$ and $i(0)$, the initial conditions of the circuit [8].

3.2. The response of series RLC circuit under sinusoidal AC excitation

In the case of smartphone charging, the circuit works under the excitation of a sinusoidal AC power supply. The series RLC circuit under sinusoidal AC excitation is shown in Figure 3.

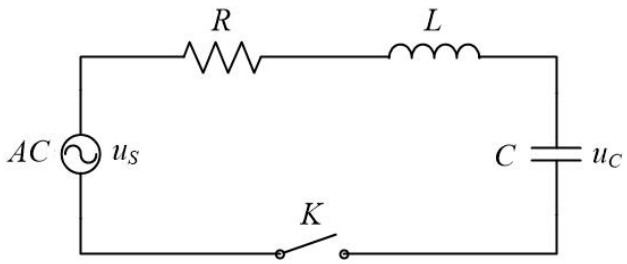


Fig. 3 The series RLC circuit under sinusoidal AC excitation (Photo/Picture credit: Original)

Set the sinusoidal AC voltage as

$$u_s = U_{sm} \sin(\omega t + \varphi_s) \tag{12}$$

If the switch K is closed when t = 0, the differential equation of the circuit is

$$LC\frac{d^2u_C}{dt^2} + RC\frac{du_C}{dt} + u_C = u_s \tag{13}$$

The special solution of equation (13), the steady-state response component of the circuit, is obtained according to the vector analysis method.

$$u_{Cp} = U_{Cm} \sin(\omega t + \varphi_C) \tag{14}$$

where

$$U_{Cm} = \frac{U_{sm}}{\sqrt{R^2 + [\omega L - 1/(\omega C)]^2}} \cdot \frac{1}{\omega C} \tag{15}$$

$$\varphi_C = \varphi_s - \frac{\pi}{2} - \arctan\frac{\omega L - 1/(\omega C)}{R} \tag{16}$$

The homogeneous equation corresponding to equation (13) is equation (5). Its general solution can be divided into three cases: overdamped state, critically damped state and underdamped state according to the comparison of the values of α^2 and ω_0^2 described in section 3.1. They are expressed as equations (9), (10), and (11), respectively. Therefore, the solution of equation (13) can also be discussed in the three cases.

When $\delta^2 > \omega_0^2$, the circuit is overdamped, and the solution of equation (13) is.

$$u_C = u_{Ch} + u_{Cp} = A_1 e^{\lambda_1 t} + A_2 e^{\lambda_2 t} + U_{Cm}\sin(\omega t + \varphi_C) \tag{17}$$

When $\delta^2 = \omega_0^2$, the circuit is in a critically damped state, and the solution of equation (13) is.

$$u_C = u_{Ch} + u_{Cp} = A_3 e^{-\delta t} + A_4 t e^{-\delta t} + U_{Cm}\sin(\omega t + \varphi_C) \tag{18}$$

When $\delta^2 < \omega_0^2$, the circuit is underdamped, and the solution of equation (13) is

$$u_C = u_{Ch} + u_{Cp} = e^{-\delta t}(A_5\cos\alpha t + A_6\sin\alpha t) + U_{Cm}\sin(\omega t + \varphi_C) \tag{19}$$

The coefficients A_1, A_2, A_3, A_4, A_5, and A_6 in equations (17), (18), and (19) are determined by $u_C(0)$ and $i(0)$, the initial conditions of the circuit. Let $u_C(0) = U_0$, $i(0) = I_0$, then.

$$A_1 = \frac{I_0 - I_{Cm}\cos\varphi_C - \lambda_2 C(U_0 - U_{Cm}\sin\varphi_C)}{C(\lambda_1 - \lambda_2)} \tag{20}$$

$$A_2 = \frac{I_0 - I_{Cm}\cos\varphi_C - \lambda_1 C(U_0 - U_{Cm}\sin\varphi_C)}{C(\lambda_2 - \lambda_1)} \tag{21}$$

$$A_3 = U_0 - U_{Cm}\sin\varphi_C \tag{22}$$

$$A_4 = \frac{I_0 - I_{Cm}\cos\varphi_C}{C} + \delta(U_0 - U_{Cm}\sin\varphi_C) \tag{23}$$

$$A_5 = \frac{I_0 - I_{Cm}\cos\varphi_C + \delta C(U_0 - U_{Cm}\sin\varphi_C)}{C\alpha} \tag{24}$$

$$A_6 = U_0 - U_{Cm}\sin\varphi_C \tag{25}$$

It is concluded by analyzing the structure of equations (17), (18), and (19) that there are two situations in the changing process of voltage and current when the circuit is turned on. One is that the voltage and current change drastically at first, that is, they go through a transient process and then enter a steady-state process. The other is that the voltage and current enter the steady-state process directly. In the first situation, overvoltage and overcurrent may occur in the transient process of the circuit. In the second one, the function of the voltage is equation (14), and the function of the current is $i_{Cp} = I_{Cm}\sin(\omega t + \varphi_C')$。

The condition for the circuit to enter the steady-state process directly is the transient component $u_{Ch} \equiv 0$ in equations (17), (18), and (19), which requires that the coefficients A_1, A_2, A_3, A_4, A_5, and A_6 in equations (17), (18), and (19) are all 0. According to equations (20), (21), (22), (23), (24), and (25), when

$$\begin{cases} U_0 - U_{Cm}\sin\varphi_C = 0 \\ I_0 - I_{Cm}\cos\varphi_C = 0 \end{cases}, \tag{26}$$

A_1, A_2, A_3, A_4, A_5, and A_6 are all 0. According to equation (16), the φ_C in equation (26) depends on the initial phase φ_s of sinusoidal AC excitation. This shows that whether the RLC series circuit under sinusoidal AC excitation can directly enter the steady-state process after being turned on depends on two factors. One is the circuit initial values U_0 and I_0. The other is the initial phase φ_s of the sinusoidal AC excitation [9].

4. The challenges and development of fast charging technology

With the popularization of smartphone fast charging technology, fast charging technology is facing more challenges. In order to meet the requirements of users for faster charging speed, it is necessary to develop more advanced fast charging technology to support greater charging power. However, increasing the charging power can lead to more heat generated by batteries, chargers and other components, and increase the loss of energy. Therefore, it is necessary to consider more effective control of the temperature of the components on the charging link. Increasing the charging power can also damage the battery, shorten the battery life and reduce the safety. Improving the charging speed, controlling the temperature rise and maintaining the health of the battery bring challenges to the power management technology [10]. In addition, the lack of unified fast charging technical standards and the different charging adapters and interfaces of various manufacturers cause the waste of adapters and charging lines and aggravate the environmental pollution.

In order to meet these challenges, various manufacturers are increasing their investment in the development of fast charging technology, and fast charging technology is developing rapidly. In the future, greater charging power will be achieved and charging time will be further shortened. Battery makers are focused on improving battery materials, which will make smartphone batteries larger, longer and safer. Power management technology will be more intelligent and more effective in balancing charging speed, temperature control and safety. Smartphones and chip manufacturers will work more closely to unify charging protocols as much as possible and reduce the variety of charging adapters and charging lines [11]. Wireless fast charging technology will develop rapidly. By improving the charging efficiency and increasing the charging distance, wireless fast charging will provide users with a more convenient charging experience.

5. Conclusion

In conclusion, fast charging technology represents a pivotal approach to significantly reduce charging durations by amplifying either the charging voltage or the charging current. The successful implementation of this technology hinges upon the integrated circuitry embedded within fast chargers. Among these components, the series RLC circuit emerges as a critical element. Within the context of smartphone fast charging, the series RLC circuit operates under the influence of sinusoidal AC power supply. Its response to this excitation comprises two fundamental components: the steady-state component and the zero-input response component. This response can be further classified into three distinctive states: overdamped, critically damped, and underdamped.

The transition of the circuit into a steady state depends on the initial conditions of the circuit and the initial phase of the power supply, which can either entail a transient process before reaching steady-state or direct entry into the steady-state following sinusoidal AC excitation. Nonetheless, the landscape of smartphone fast charging technology is not without its challenges, including the imperative need for shorter charging times, managing increased energy consumption, mitigating potential battery damage, and addressing the issue of inconsistent charging protocols.

As look to the future, fast charging technology holds the promise of delivering an enhanced user experience, bridging the gap between the growing demands of modern smartphone users and the technological advancements required to meet these demands.

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