Analysis and Design of High-Intensity-Discharge Lamp Ballast for Automotive Headlamp

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(ABSTRACT)

The High-Intensity-Discharge Lamps (HID), consisting of a broad range of gas discharge lamps, are notable for their high luminous efficacy, good color rendering, and long life. Metal halide lamps have the best combination of the above properties and are considered the most ideal light sources. Recently, there has been an emerging demand to replace the conventional halogen headlamps with the newly introduced small-wattage metal halide HID lamps. However, this lamp demands a highly efficient ballast and very complex control circuitry that can achieve fast turn-on and different regulation modes during the lamp start-up process.

Due to the complex lamp *v-i* profile and timing control requirements, control circuit built with conventional analog control is unavoidably cumbersome. With the unparalleled flexibility and programmability, digital control shows more advantages in this application. An automotive HID ballast with digital controller is developed to demonstrate the feasibility of the digital control along with some key issues in digital controller selection and design. Results show that the microcontroller-based HID ballast can successfully realize the required control functions and achieve a smooth turn-on process and a fast turn-on time of 8 seconds.

One of the major issues of ballast design is the ballast/HID lamp system stability, which originates from the lamp negative incremental impedance. The lamp small-signal model is presented with simulation and measurements. The negative incremental impedance is attributed to a RHP zero in the small-signal model. A new analysis approach, *impedance ratio criterion*, is proposed to analyze the system stability. With this approach, it clearly shows how the control configurations and converter and control design affect the system stability. The results can provide guidance and be easily used in control configuration selection and converter and control design. Analysis shows that ballast based on PWM converter without inner current loop is unstable and with inner current loop can stabilized the system. This is the reason why for a microcontroller-based ballast system the inner current loop has to be used.

HID lamp has its special acoustic resonance problem and thus a low-frequency unregulated full-bridge is used following the front-end DC/DC converter. To prevent from lamp re-igniting during each bridge commutation, a minimum current changing slope has to be guaranteed. In order to help design the converter, the ballast/lamp re-ignition analysis is presented. With this analysis, it shows that the output capacitance has to be small enough to ensure adequate current slope during zero crossing. Though some approximation is used to simplify the analysis, the results can provide qualitative guidance in the ballast design.

To my parents, wife and son

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1. Introduction

1.1 High Intensity Discharge (HID) Lamps

Electric lamps have been known for more than 100 years. This is true not only for incandescent lamps, which are still widely used, but also for gas discharge lamps for street lighting. These, however, could not hold their own in the long run. The carbon electrodes between which the electric discharge took place had to be regularly renewed, which proved too expensive at that time. Another 50 years went by, after the introduction of incandescent lamps, before the first electric discharge lamps for general lighting purposes were able to demonstrate their practical usefulness [1]-[3].

Because gas discharge lamps generate much less heat while emitting lights, they are inherently much more efficient than incandescent lamps. Present-day lighting techniques are inconceivable without the wide variety of members of the gas discharge lamp family. In buildings, offices, and factories, for instance, we find many thousands of tubular fluorescent lamps. Besides these fluorescent lamps, which is generally categorized as low-pressure gas discharge lamps, there are a broad range of high intensity discharge (HID) lamps, i.e., which are filled with high-pressure gas. According to the gas composition, existing HID lamps are usually classified into three types, high-pressure mercury lamps, high-pressure sodium lamps, and metal halide lamps.

One of the most important aspects of light generation, certainly from the application point of view, is the *luminous efficacy* of a lamp. The luminous efficacy is defined as the ratio of the luminous flux of a light source to the power dissipated in it and expressed in lumens per watt (lm/W). Another equally important factor for choosing HID lamps is the color properties of the light source, which is usually referred to as color rendering. A good color rendering means even spectral energy distribution in the visible part of the electromagnetic spectrum and thus close to daylight.

The visible radiation of high-pressure mercury discharge is concentrated in a few spectral lines that are unevenly distributed over the visible part and some of the ultraviolet part and thus tend to be blue, which is also not favorable in terms of lumen efficacy. To get better color rendering, this ultraviolet radiation can be converted from ultraviolet radiation to visible radiation by a fluorescent powder layer on the inside wall of the bulb to supply the red component absent in the original radiation. Such process, however, always involves a loss of energy. High-pressure sodium lamps, on the contrary, tend to be red and its lumen efficacy is just moderately high. By filling up the gaps in the spectral energy distribution in the visible part with radiation from other metals and some halide components, metal halide HID lamps exhibit the best combination of high lumen efficacy, good color rendition and long life. Among these three types of HID lamps, metal halide lamps have the best luminous efficacy and color rendering, which makes them better light sources where people need good artificial lighting, such as stadiums, stages, and photography.

1.2 Automotive HID Lamp Advantages and Challenges

Recently, there has been an emerging demand to replace the conventional halogen headlamps with the newly introduced small-wattage metal halide HID lamps [4][5]. Compared to the conventional halogen headlamps, these HID lamps offer 5 times better lumen efficacy (as shown in Figs. 1.1 and 1.2), better color rendering (as shown in Fig. 1.1), better focusing capability, and longer life (5000 hours vs. 1500 hours). These superior performances soon make them popular in some high-end cars.

However, this special lamp has its special issues and present some challenges in both converter design and ballast control. These lamps need a very complex ballast circuitry to deal with the special transient characteristics and an efficient DC/DC converter because of the expensive thermal management. This is why these automotive HID headlamps are only optional to luxury cars right now.

Initially, it needs a high voltage pulse for ignition (for Philips D2S 35 W lamp, 2 kV for cold start and 25 kV for hot re-strike). And then a large take-over current should be supplied to the lamp in order to make the lamp transit from the glow discharge state to the arc discharge state. Once the lamp enters into arc discharge state, each electrode needs a relatively long period current to warm up and maintain the arc. Then the ballast need to provide enough power, which is much more than steady state power, to ensure fast transition to steady state to meet the safety requirements. Finally, in steady state, power should be properly controlled (constant power preferred) due to the lamp characteristics variations with manufacturing and aging.

(a) (b)

Fig. 1.1 Comparison of the road views of (a) conventional halogen headlamp and (b) metal halide HID headlamp.

	Standard Halogen Bulb	**HID Light Source**
Light Source	**Filament**	**Arc Discharge**
Color Temperature	**~3,000° K**	**4,100° K**
Lumens/Light Output	**700 - 1,000**	**3,200**
Light Source Watts	**55W**	**35W**
Life	**320 - 1,000 hours**	**Up to 3,000 hours**

Fig. 1.2 Comparison chart between halogen and metal halide HID headlamps.

Therefore, the ballast must be capable of configuring different control modes according to the lamp condition and realizing the complex timing, otherwise lamp cannot start and work properly. Conventional analog control can hardly fulfill all these requirements. Even if it can achieve all the above control functions, the circuits are unavoidably too complex with analog control circuits. With the superior advantages of flexibility, digital control is better choice in this application. As we can demonstrate, digital control can achieve not only all the control and timing functions required but also optimum start-up control to reduce the turn-on time.

In order to avoid continuous electrode material loss, AC drive is required. Unlike fluorescent lamps, metal halide lamps have special acoustic resonance problem. So, we have to drive the lamp at some certain low resonance-free frequency range. Even some work has been reported for MHz range operation of HID lamp, EMI issues and efficiency consideration make it an undesirable engineering solution. So in this thesis, we are only focusing on low-frequency square-wave AC drive.

Due to the extreme ambient temperature range and expensive thermal management, it is highly desirable to improve the efficiency of the ballast. Because the front-end is a dominant part of the whole circuit in terms of efficiency, it has to be carefully selected and designed.

1.3 Organization of the Thesis

The research work reported here focuses on the following two tasks.

1) Development of a digitally controlled HID ballast system.

2) Development of gas discharge lamp small-signal model and analysis of ballast/lamp system stability issues in the presence of the lamp negative incremental impedance.

The major contributions of the research work described in this thesis are listed below:

1) Developed a digitally controlled automotive HID ballast system. The HID lamp characteristics are analyzed in details first to demonstrate the complexity of the control design for automotive HID ballast. Then a digital controller is designed and implemented to demonstrate the advantages over analog counterpart in this application.

2) Presented a systematic frequency-domain small-signal model of gas discharge lamps that can be easily used in ballast control design. The new models are verified by both simulation and experiment.

3) Presented the lamp commutation analysis and some relationships between ballast circuit and lamp re-ignition failure during commutation. This model is also verified by simulation and experiment.

The thesis is divided into five chapters with an introduction at the beginning, which provides some background material of HID lamps and advantages of automotive HID headlamps and challenges of the ballast design.

Chapter 2 presents the ballast/lamp system analysis. After analyzing the lamp operation during each stage of start-up process, the ballast circuit and control requirements are presented. The lamp commutation process is analyzed to provide some guidance for ballast circuit design.

In Chapter 3, the digital control implementation is presented. After discussing the comparison between analog control and digital control, one feasible digital control scheme is identified. Several digital control issues are presented along with the selection process of digital controller. As a result, a smooth turn-on process and a fast turn-on time were achieved with an optimum control algorithm.

Chapter 4 presented the small-signal analysis of ballast/HID lamp system. In order to properly design and control the ballast, the lamp small-signal model is investigated first. The negative incremental impedance is represented by a right-half-plane zero in frequency domain. A new analysis approach, closed-loop output impedance, is proposed to analyze the system stability. With this approach, it clearly shows how the control configurations and converter and control design affect the system stability. The results can provide guidance and be easily used in control configuration selection and converter and control design. Analysis shows that ballast based on PWM converter without inner current loop is unstable and with inner current loop can stabilized the system. This is the reason why for a microcontroller-based ballast system the inner current loop has to be used.

Finally, conclusions are obtained based on the research work and some suggestions for future work are outlined in Chapter 5.

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2. Automotive HID Ballast/Lamp System Analysis

2.1 Automotive HID Lamp Characteristics

2.1.1 Automotive HID Lamp Start-up V-I Profile

This low-wattage HID lamp is specially designed for automotive use for quick start and hot re-strike. Special care must be taken for proper start-up and operation. Fig. 2.1 qualitatively shows the lamp voltage and current profile during the lamp six operation stages: turn-on, ignition, take-over, warm-up, run-up, and steady state. The ballast should follow this profile to ensure lamp's proper operation and expected life. As we will see the lamp is a very complex load to drive, which needs not only different control modes for different stages but also complicated timing control. The operation analysis is provided below along with the requirements from the ballast point of view.

(1) Turn-on stage (T_1 » 30 ms):

Before the lamp gas breaks over, it operates like an open circuit. In order to generate the ignition pulse from the igniter and also guarantee reliable takeover, especially for hot re-strike (which is crucial for automotive application), a minimum voltage of 360 V is required. So the ballast needs to provide a constant voltage and maintain for a few tens of milliseconds during this stage.

(2) Ignition stage (T2 » 100 ns):

The lamp can be safely turned on with an ignition pulse of as high as 23~30 kV depending on the lamp type, lamp conditions (both temperature and aging), and also the rise-time of the pulse. An additional specially designed igniter is needed to generate the high voltage pulse.

(3) Take-over stage (T3 » 300 ms):

Once the ignition pulse breaks through the lamp, the lamp impedance will drastically drop to a few tens of ohms. The lamp requires a high initial current of 12 A maximum for a short time in order to sustain the arc before the ballast can react to the ignition. This current is referred to as the takeover current and is delivered by discharging some energy storage capacitor into the arc. The required discharge time constant is in the range of a few hundreds of microseconds. The take-over capacitor will pre-charge during turn on and deliver the inrush current immediately after the ignition.

(4) Warm-up stage (T4 » 20 ms):

After arc break-over, the lamp behavior is strongly dependent on its temperature. A hot lamp will exhibit an initial voltage of about 85 V, while a cold one can be as low as 20 V. For the cold lamp, the lamp must be warmed up to be able to supply enough electrons for conduction immediately after the current inrush. This is done by injecting a maximum 2.6 A dc current into the lamp, which yields a time integral of about 20 mAs for each polarity. Since in this period each polarity is much longer than the steady state, it is also called dc phase. This stage is very crucial for the lamp proper operation. Without it, the lamp may extinguish at a subsequent stage of higher operation frequency. And the frequency change adds some difficulty to the control implementation.

(5) Run-up stage (T5 » 10 s):

The automotive lamp has to be driven in order to meet the SAE specification for the light output vs. time. While the steady state power is 35 W, the transient power needed to achieve the required output characteristics when driving a cold lamp can be as high as 75 W. It is characterized by a maximum current (2.6 A) and maximum power (75 W) delivered into the lamp for electrode temperature considerations. During the run-up, the voltage across a cold lamp comes up from 20~30 V to nominal 85 V at steady state. While a warm lamp may start from anywhere between 20 V and 85 V. Therefore there arises the issue on how to detect the lamp condition and achieve the optimal control for a shortest run-up period for lamps of any condition. Also, the lamp will experience a steady increase of voltage along with the decrease of current.

We need to look into how to drive the lamp with the fastest transient while below the current/power limits.

(6) Steady state (T6):

After 6~12 seconds, a cold lamp will enter steady state. The lamp steady state voltage depends on the individual lamp characteristics and aging. The nominal steady state voltage is 85 V, but there is a spread of ±17 V. It is highly recommended to operate the lamp at a nominal 35 W to obtain the best lifetime performance. A too high power will damage the lamp and thus shorten the lifetime and too low power may cause arc instable or even extinction and low lumen output. There is a ±2 W power regulation requirement.

2.1.2 Acoustic Resonance and Ballast Structure

One of the major limitations of HID lamps is that their steady state operation at frequencies higher than some kilohertz suffers from the effect of *acoustic resonance*, which causes unstable arc, flicker, arc extinguishing, and even lamp destruction. The acoustic resonance phenomenon depends on the lamp geometry, gas temperature and pressure inside the lamp bulb. Analysis shows that for this low-wattage HID lamp there are no resonance-free frequency sub-ranges from about 10 kHz to 1 MHz. Megahertz operation of HID lamp ballast can be possible. However, it is generally less efficient and problematic EMI issues make it an unpopular option. For this reason, we use low-frequency square-wave AC drive to avoid the acoustic resonance problem. Thus, the ballast system has a full-bridge following the front-end DC/DC converter as shown in Fig. 2.2. Thus, in this thesis, we are only focusing on the two-stage ballast structure.

The choice of the full-bridge operating frequency is straightforward. Since it has no regulation function at all, the frequency should be as low as possible to reduce the switching loss in this stage. And the lower end is limited by any presence of any flicker effect, which in practice is a few hundred hertz (recommended 250 Hz by manufacturer). In practices, a frequency about 400 Hz is chosen.

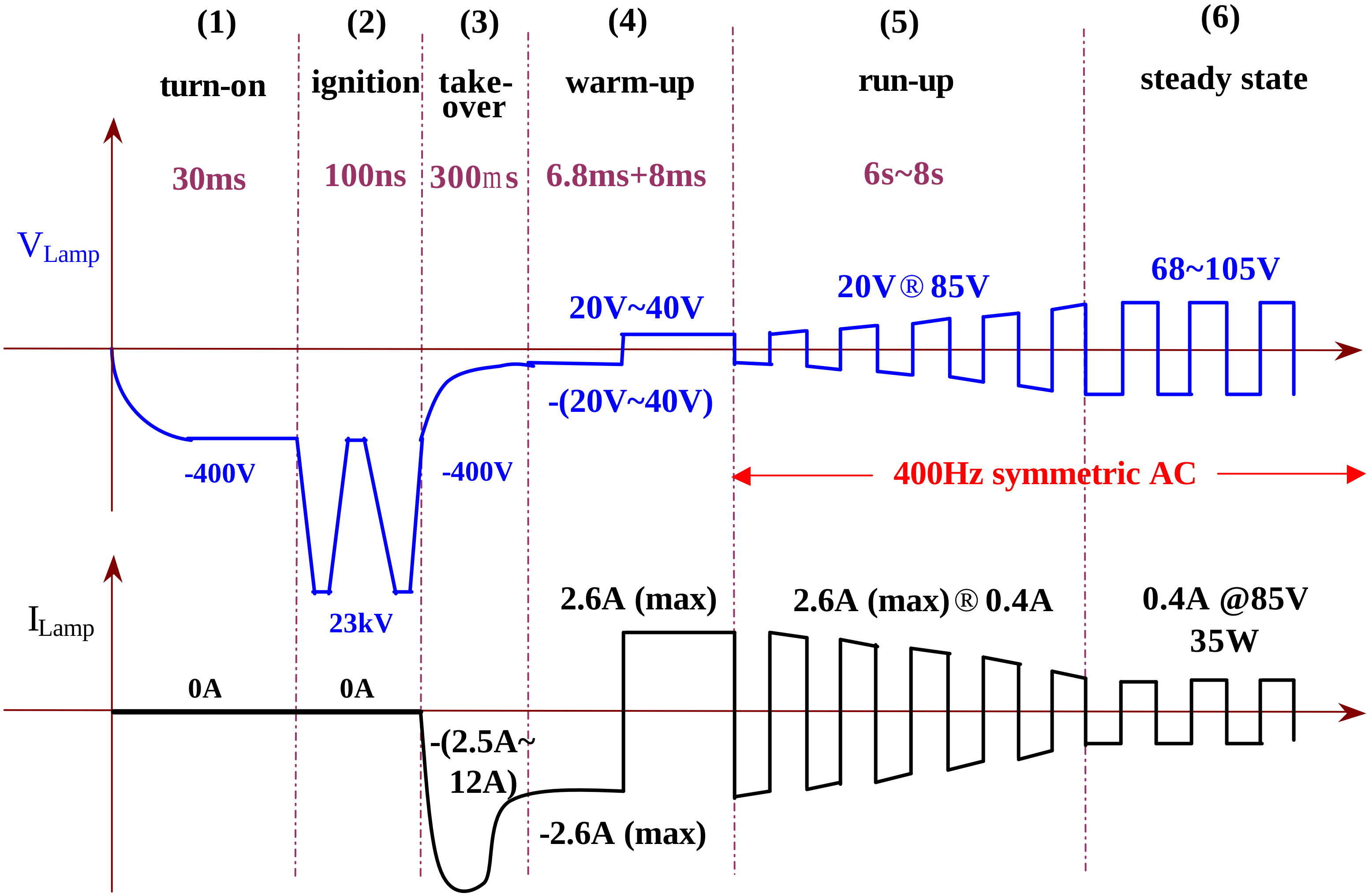

Fig. 2.1 Lamp V-I profile in all phases of operation (qualitatively, not in scale).

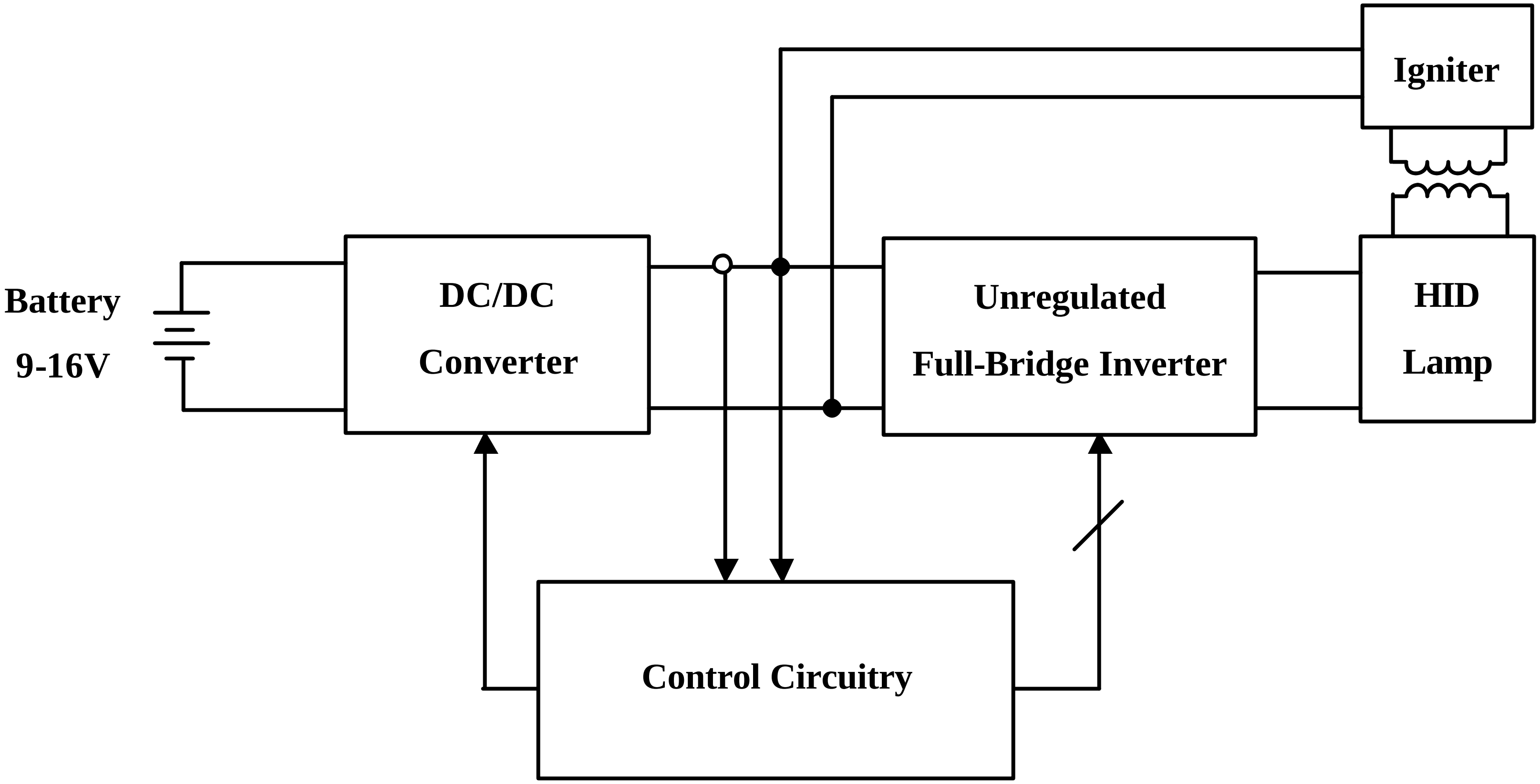

Fig. 2.2 Automotive HID ballast system diagram.

Table 2.1 Summary of lamp operation

Phase	Parameter	Value
Turn-on	Open circuit voltage	360 V (min.)
	Turn-on time	About 30 ms
Ignition	Ignition voltage	23 kV min. (for hot lamp)
	Pulse duration	1 s max.
	Repetition rate	20 Hz min.
Take-over	Take-over current	2.5 A (min.) to 12 A (max.)
	Take-over time	300 µs max.
Warm-up	Warm-up current integral	12 (min.) ~ 30 (max.) mA·s
	Current	2.6 A max.
	Warm-up time	About 10 ms each halfwave
Run-up	Run-up current	2.6 A max.
	Run-up power	75 W max. until V_{lamp} reaches 50 V
	Run-up time	6 ~ 12 s
Steady state	Power	35 W (±2W)
	Voltage	68 ~ 102 V
	Frequency	250 ~ 10000 Hz
	Square wave asymmetry	< 1 %
	Lamp current slope (zero crossing)	100 mA/µs min.

2.1.3 Requirements for the Ballast Circuit and Control

From the above analysis, we can see that ballast need to work at different modes at different stages. Specifically, at turn-on stage, the ballast should output a proper output voltage and maintain it for some time until the igniter generates the ignition pulse. So, it needs to feed back the output voltage and configured as voltage-feedback control mode as shown in Fig. 2.3.

Then at warm-up stage, the ballast should control the lamp current and current integrals for each half wave until the integral reaches some preset value. So, it needs to feed back the lamp current and configured as current-feedback control mode as shown in Fig. 2.4.

Finally at run-up and steady state, the ballast should properly control the lamp power. First the power cannot exceed 75 W and the current cannot exceed 2.6 A. So if the initial voltage is below 30 V, the ballast should limit the output current to its maximum allowable value until the lamp power reaches 75 W and it's still work as current-feedback mode. Once the lamp power goes above 75 W, the ballast should be programmed as constant power controller. And this constant power should be maintained until the voltage reaches to about 50 V. Then the lamp power should gradually decrease to the steady state level, 35 W. So in these two stages, it's mainly power-feedback control and current-feedback control may exist depending on the lamp initial condition. The power-feedback control mode is shown in Fig. 2.5.

A proper control sequence is shown in Fig. 2.6 with proper lamp voltage, current, and power level indicated. Since both lamp voltage and current are sensed in the DC side and the AC values are approximately the same, they all shown in DC values. While lamp power is just the product of DC voltage and current.

In Fig. 2.6, different control modes are marked with different color. It should be noted that this is for the most common case, i.e., for a cold lamp. While for a hot lamp, the lamp may have a high initial voltage immediately after ignition and some control modes should be skipped. Since the start-up process is highly dependent on the lamp aging and condition, it is highly advisable that the control could adapt to all these conditions.

From the above analysis, we can see this automotive HID lamp needs specially designed ballast to secure fast turn-on time and flexible controller to fulfill all the control task.

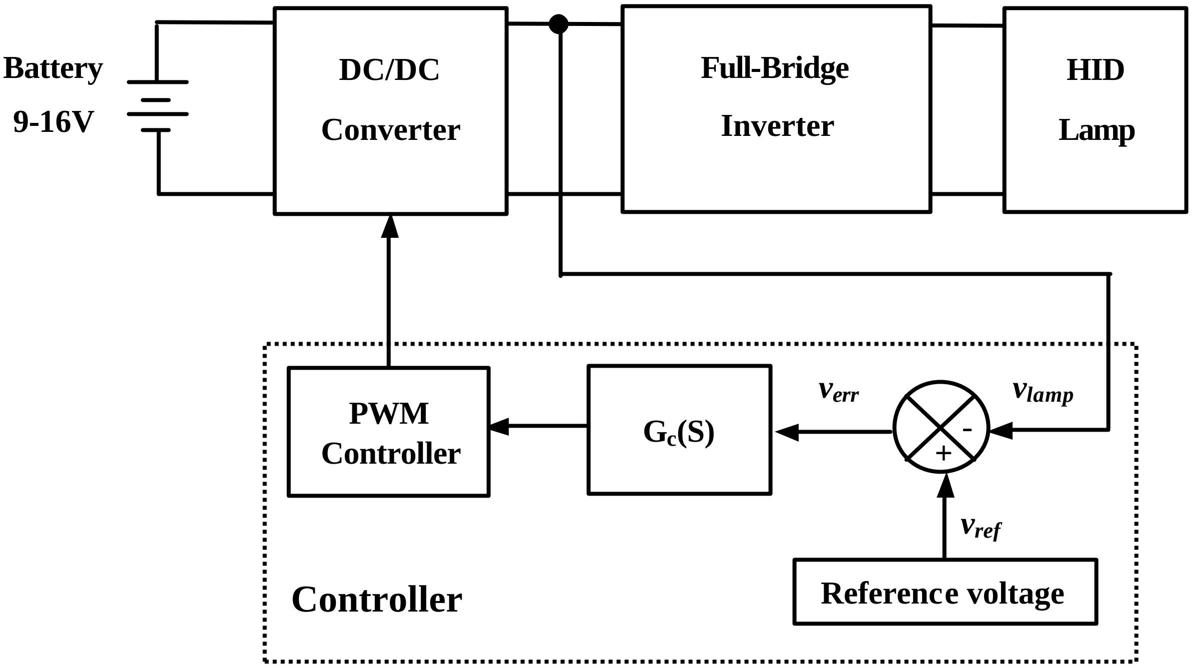

Fig. 2.3 Voltage-feedback mode control diagram.

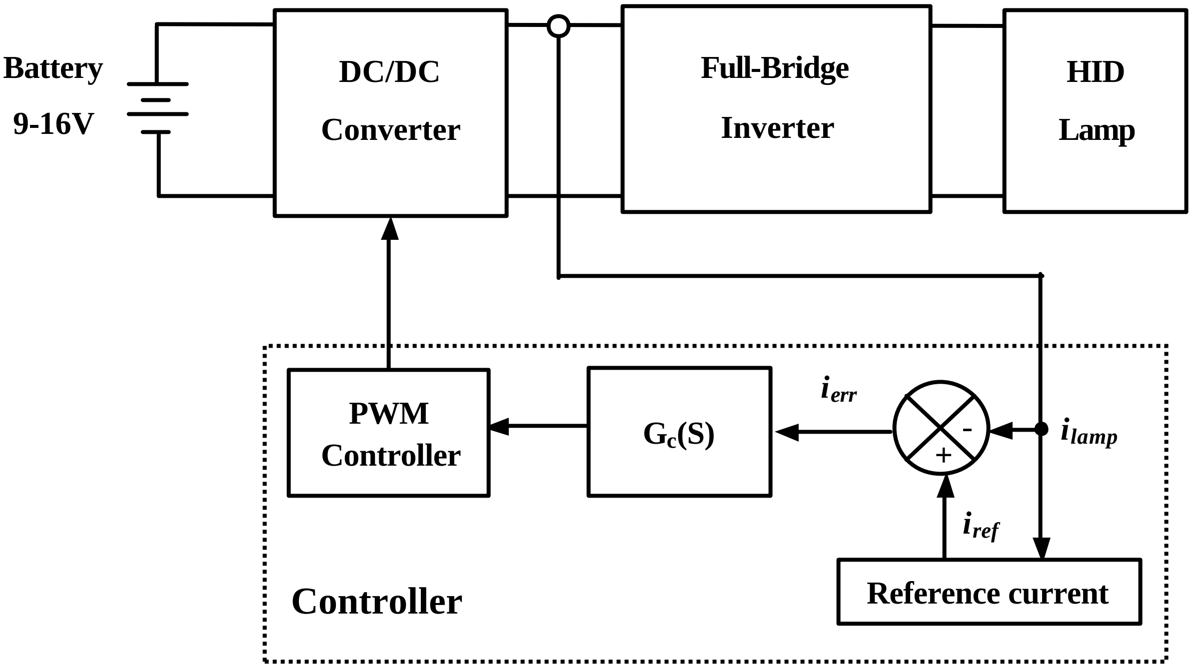

Fig. 2.4 Current-feedback mode control diagram.