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Kun Zhao
University of Wollongong

Philip Ciufo
University of Wollongong, ciufo@uow.edu.au

Sarath Perera
University of Wollongong, sarath@uow.edu.au

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Abstract

This paper evaluates the changes in the ripple current for an electrolytic capacitor used in the dc-side of a single-phase rectifier circuit when subjected to input voltage fluctuations. The study has been undertaken in order to analyse the potential impact on capacitor lifetime. The key effect is that the capacitor ripple current, as a consequence of voltage fluctuations, increases dramatically and this phenomenon keeps deteriorating as the frequency of the voltage fluctuations increases. Simulations and experimental work confirm this phenomenon. Since the power loss and temperature rise are dependent on the capacitor equivalent series resistance (ESR) and ripple current components, an increase in ripple current under voltage fluctuation conditions is likely to accelerate this process, resulting in a reduced lifetime.

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Lifetime Analysis of Aluminum Electrolytic Capacitor Subject to Voltage Fluctuations

Kun Zhao, Philip Ciufo, *Senior Member, IEEE*, and Sarath Perera, *Member, IEEE*

***Abstract*—This paper evaluates the changes in the ripple current for an electrolytic capacitor used in the dc-side of a single-phase rectifier circuit when subjected to input voltage fluctuations. The study has been undertaken in order to analyse the potential impact on capacitor lifetime. The key effect is that the capacitor ripple current, as a consequence of voltage fluctuations, increases dramatically and this phenomenon keeps deteriorating as the frequency of the voltage fluctuations increases. Simulations and experimental work confirm this phenomenon. Since the power loss and temperature rise are dependent on the capacitor equivalent series resistance (ESR) and ripple current components, an increase in ripple current under voltage fluctuation conditions is likely to accelerate this process, resulting in a reduced lifetime.**

***Index Terms*—Voltage fluctuation, flicker, rectifier current ripple, electrolytic capacitor, ESR**

I. Introduction

Voltage fluctuations are defined as repetitive or random variations in the magnitude of the supply voltage. These fluctuations are caused by variations in the power consumed by loads whose power demand is not constant in time, or by the connection or disconnection of loads. Examples of loads that can cause voltage fluctuations include starting of high-power motors, operation of capacitors for power factor correction, [1] [2] [3] etc. A consequence of voltage fluctuations is light flicker. Light flicker is an impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time [4]. Flicker can be used to indicate the level of voltage fluctuations. The level of flicker depends on the amplitude, frequency and duration of voltage fluctuations. Many devices, especially the incandescent lamp, are sensitive to voltage fluctuations.

The incandescent lamp is slowly being replaced by other, higher efficiency lamp types in the residential lighting market, e.g. compact fluorescent and other energy saving lamps. The Australian Government has announced that incandescent lamps are to be phased out and eventually banned [5]. Since different lamp types utilise different technologies, the flicker response of these lamp types are significantly different. Research conducted on the flicker response of new lamp types are documented in [5] [6] [7]. Studies show that the new lamp types are less sensitive to voltage fluctuations than the conventional incandescent lamp. The results obtained could be used to support a discussion about a relaxation the recommended or normative flicker index limits.

However, the potential detrimental effects caused by voltage fluctuations on electrical equipment should be considered before the flicker limits are relaxed. The Switch Mode Power Supply (SMPS) has been widely utilised in modern electronic equipment because of the merits of high efficiency and compact size. As an indispensable, cost-effective component, the single-phase diode bridge rectifier combined with a smoothing capacitor, is widely used at the input stage of switch mode power supply. As these components are directly connected to the public supply network, the impact on this circuit from supply voltage fluctuations is of primary interest.

The features of large capacitance, high energy storage and low price means that aluminium electrolytic capacitors are often used in the dc-bus side of a rectifier for reducing voltage ripple. Unfortunately, the electrolytic capacitor is responsible for most of the failures of power supplies and its short life span normally cannot meet the requirement for long-life system design [8] [9]. The relative analyses of aluminium electrolytic capacitors under normal power supply conditions are presented in several papers [10] [11] [12]. However, a comprehensive analysis of the stress on the dc-bus electrolytic capacitor under voltage fluctuations has not been studied in great detail. As will be shown, input voltage fluctuations can lead to high currents in the capacitor. Attention in this paper is focused on the rectifier behaviour under voltage fluctuations, especially the impact of the rectifier current on the capacitor life span under fluctuating voltage conditions.

This paper is organised into several sections to analyse this problem. Voltage sources with fluctuation which can frequently occur in ac systems are briefly reviewed in order to model the appropriate voltage excitation to observe rectifier behaviour, as shown in Section II. The circuit of a single-phase rectifier with capacitor filter is analysed under voltage fluctuations and relative capacitor ripple current simulation results are presented in Section III. The power loss mechanism, thermal model and lifetime prediction for an electrolytic capacitor are introduced in Section IV. Section V is a summary of this paper and a description of further work.

II. Review of Voltage Fluctuations

The term flicker is derived from the impact of voltage fluctuations on incandescent lamps such that they are perceived by the human eye to light flicker. Flicker is also an undesirable result of voltage fluctuations caused by some loads. Thus, the term flicker is used to indicate and describe the

Kun Zhao, Philip Ciufo, and Sarath Perera are with the School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, and are Members of the Integral Energy Power Quality and Reliability Centre, NSW 2522, Australia (email: kz664@uow.edu.au, ciufo@uow.edu.au and sarath@uow.edu.au).

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voltage fluctuations phenomenon. The flicker frequency can be perceived by the eye-brain from 0.5 Hz to approximately 32 Hz. It generally has a detrimental physiological effect on humans, causing annoyance or eye strain [5].

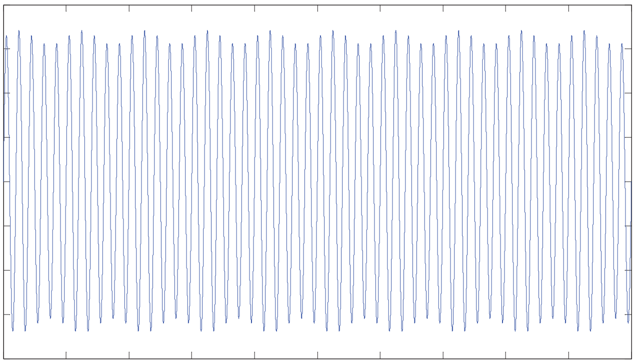


Fig. 1. Typical voltage fluctuations profile

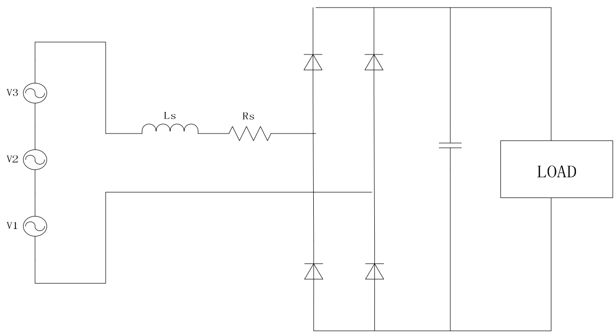


Fig. 2. Rectifier model under voltage fluctuations condition

Fig. 1 illustrates a typical voltage fluctuations profile. According to [13], the voltage modulation can be divided into two classes: sinusoidal and rectangular voltage fluctuations. In this paper, the focus is on studying the rectifier effects caused by a source voltage with sinusoidal modulation.

When subjected to voltage fluctuation operating conditions, if ΔV expresses the peak-to-peak voltage variation and V is the fundamental voltage mean peak value, then an expression can be derived to relate voltage change, $\Delta V/V$, at a given frequency, f_m, for the case of sinusoidal modulation. It should be noted that the changes in rms values are essentially equal to the time function voltage changes. Thus, the power supply with voltage fluctuations can be represented as:

$$v(t) = \sqrt{2}V_{rms}\sin(\omega_c t)[1 + \frac{1}{2}\frac{\Delta V}{V}\sin(\omega_f t)] \quad (1)$$

where $v(t)$ is the power supply voltage with a fluctuation which is modulated by the different amplitude and frequency levels. V_{rms} is the fundamental voltage rms value. Fundamental angular frequency is expressed by ω_c and modulation angular frequency is ω_f. The following equation can be obtained through expanding (1):

$$\begin{aligned} v(t) &= \sqrt{2}V_{rms}\sin(\omega_c t) + \frac{\sqrt{2}}{2}\frac{\Delta V}{V}V_{rms}\sin(\omega_c t)\sin(\omega_f t) \\ &= \sqrt{2}V_{rms}\sin(\omega_c t) + \frac{\sqrt{2}}{4}\frac{\Delta V}{V}V_{rms}\sin[(\omega_c + \omega_f)t - \frac{\pi}{2}] \\ &+ \frac{\sqrt{2}}{4}\frac{\Delta V}{V}V_{rms}\sin[(\omega_c - \omega_f)t + \frac{\pi}{2}]. \end{aligned} \quad (2)$$

Therefore, a power supply that can provide voltage fluctu-

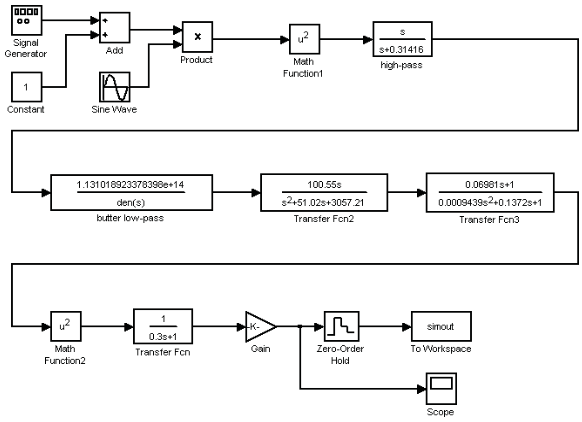


Fig. 3. MATLAB/Simulink® flickermeter model

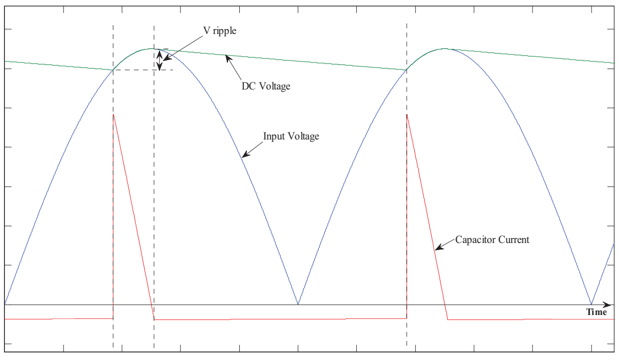


Fig. 4. Rectifier characteristic with a sinusoidal supply

ations can be simulated using three, ideal sinusoidal voltage sources connected in series as is illustrated in Fig. 2.

As documented in [4] and [13], the severity of voltage flicker can be indicated by the *short-term flicker severity*, P_{st}, and the *long-term flicker severity*, P_{lt}. The device used to quantify these metrics is called the flickermeter. The IEC flickermeter is well known device.

The flickermeter structure and design guidelines are described in [13] and [14]. Therefore, a flickermeter model can be established by using MATLAB/Simulink®, as illustrated in Fig. 3.

Having identified the voltage fluctuations characteristics, the effect of such a source on the operation of single-phase passive diode bridge is analysed in Section III.

III. Behaviour of Single-phase Rectifier Capacitor Ripple Current

The circuit of a typical singe-phase rectifier with capacitor filter, which is connected between the load and the power supply network, is shown in Fig. 2. Generally, the power supply includes some source impedance, which comprises a series equivalent inductance, L_s, and a series resistance, R_s.

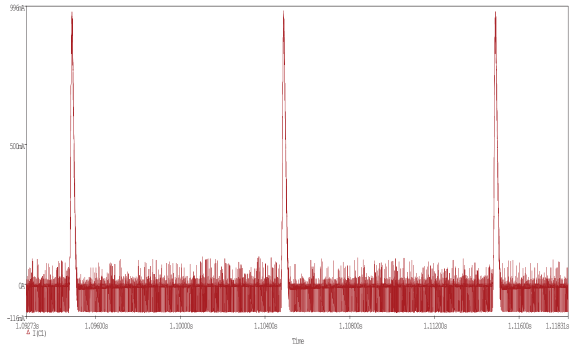


Fig. 5. Capacitor current waveform

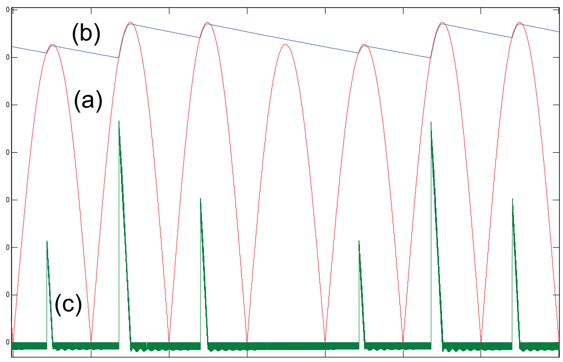


Fig. 6. Simulation waveforms of (a) input voltage (b) dc-bus voltage (c) capacitor ripple current

As is well known, the filter capacitor stores energy during the

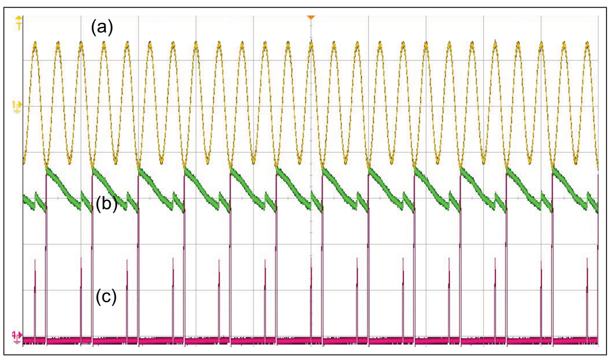


Fig. 7. Experimental waveforms of (a) input voltage (b) dc-bus voltage (c) capacitor ripple current

charging time and supplies the load during the discharging time and the load connected to the dc bus is the switch mode power converter. Therefore, the load voltage and current can be considered as constant value [16] [17]. If the source impedance is neglected, the capacitor voltage and diode current can be illustrated in Fig. 4. Under such conditions, the capacitor recharging current drawn from the supply is symmetrical and the capacitor current peak and rms values remain constant in each half cycle. These currents may include a high frequency ripple component caused by converter switching frequency effects in the SMPS, as illustrated in Fig. 5.

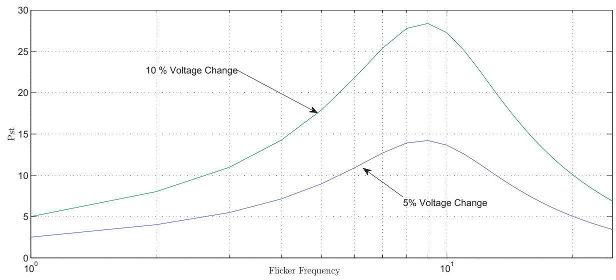
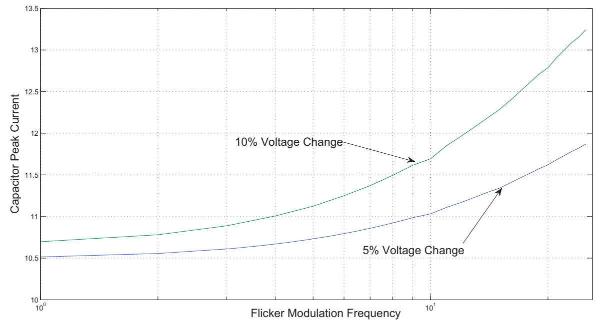
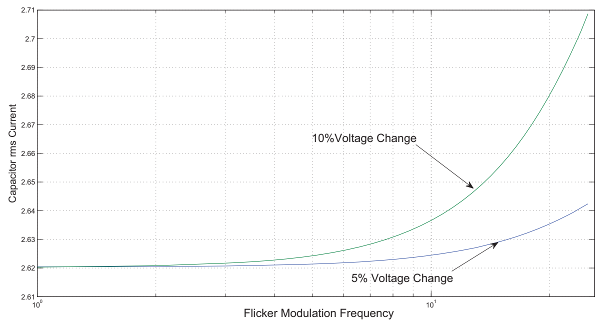


Fig. 8. P_{st} value under different voltage fluctuations condition



(a) Capacitor peak current



(b) Capacitor rms current

Fig. 9. Capacitor current value under different voltage fluctuations condition

As an illustrative simulation case, a 230 V power source with a voltage change rate of 10% and with a 25 Hz modulation frequency is used to supply a rectifier with a 235 μF filter capacitor and a 1 A load. The resulting dc-bus voltage and capacitor charging/discharging current profile are illustrated in Fig. 6. As can be seen, the dc-bus capacitor starts charging when the dc-bus voltage is below the instantaneous input voltage. Otherwise, the capacitor discharges to the load. For a rectifier circuit, the capacitor charging stops at the peak of the input sinusoidal waveform without considering the source impedance effect. When subject to supply voltage fluctuations, the dc-bus voltage waveform is modulated too. The filter capacitor ripple current is different in each half cycle and sometimes will disappear when the ac voltage peak value is less than the dc-bus voltage. Meanwhile, the filter capacitor will draw more current than normal during the recharge cycle when the ac voltage peak value is greater than the dc-bus voltage.

In order to test the validity of the simulation results, a simple experiment was performed. A rectifier/filter circuit, such as that which has been simulated, was built. The circuit was then connected to a programmable power supply. With the voltage fluctuations provided by the programmable supply, the resulting dc-bus voltage waveform and capacitor ripple current waveform, is presented in Fig. 7. Behaviour of the capacitor charging current obtained from simulation results (Fig. 6) is seen to be in close agreement with that which has been obtained from experiment results (Fig. 7).

The supply voltage fluctuations leads to the electrolytic capacitor peak recharging-current increasing dramatically at a particular cycle and causes the rms value of the cyclic recharging-current to increase dramatically as well.

For the simulated circuit, if the voltage change remains constant but different flicker frequencies are applied, the relationship between the flicker frequency and the capacitor peak and rms currents can be obtained. These are illustrated Fig. 8 and Fig. 9.

It should be noted that the filter capacitor ripple-current becomes worse as the modulation frequency increases. However, the flicker index P_{st}, is at a peak at around 9 Hz, then, the value decreases as the modulation frequency increases. Thus, the filter capacitor should be given more attention especially when subject to high modulation frequency conditions.

IV. Electrolytic Capacitor Lifetime Evaluation

Due to their relatively large capacity and low cost, aluminium electrolytic capacitors are widely used in many power electronic circuits. Although the aluminium electrolytic capacitor is the primary choice for industrial applications, it is not a perfect device. The main drawback is their reliability, especially their lifetime [10] [12] [17]. Operating temperature is the main factor causing degradation of the capacitor parameters, especially the equivalent series resistance (ESR). The ripple current and ambient temperature are the main contributors to the temperature rise of the capacitor. The significant degradation mechanisms accelerated by heating are chemical changes in the oxide layer and the electrolyte vapour leakage through the capacitor and seal. Both factors lead to an increase in ESR over the operating life of a capacitor.

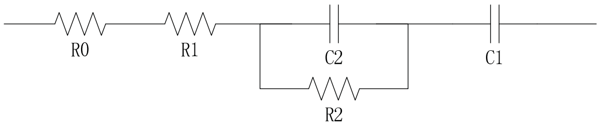


Fig. 10. Electrolytic Capacitor model [10]

Capacitor power loss and lifetime evaluation requires both modelling and experimental understanding of the capacitor characteristics. Such models need not be complex, but must represent the key characteristics that define the lifetime parameters of the capacitor. By neglecting the capacitor's leakage current an improved capacitor model, presented in Fig. 10, has been shown to match well with experimental results, including lifetime prediction [10]. The complex impedance of the electrolytic capacitor is described as [10]:

$$Z_{\text{cap}} = \frac{1}{\frac{1}{R_2} + j2\pi f C_2} + R_0 + R_1 - \frac{j}{2\pi f C_1} \tag{3}$$

where Z_{cap} is the complex impedance of the capacitor, resistance R_0 combines the resistances of foil, tabs and terminals, whilst R_1 accounts for the electrolyte. A parallel combination of R_2 and C_2 models the dielectric resistance. However, the ripple current heating occurs in the real part of the capacitor impedance. Thus, the (ESR) of electrolytic capacitor can be expressed as [10]:

$$\begin{aligned} \text{ESR} &= \text{Real}(Z_{\text{cap}}) \\ &= \frac{R_2}{1 + (2\pi f)^2 {C_2}^2 {R_2}^2} + R_0 + R_{1\text{base}} e^{\frac{(T_{\text{base}} - T_{\text{core}})}{E}}. \end{aligned} \tag{4}$$

The temperature dependent nature of the electrolytic resistance, R_1, is modelled with a base resistance, $R_{1\text{base}}$, and an exponential temperature variation controlled by a temperature sensitivity factor E. T_{base} is the temperature at which the ESR was measured and T_{core} is the temperature of interest for the ESR calculation.

The ripple-current heating losses in the capacitor are estimated based on this model. Since aluminium electrolytic capacitors have a relatively high ESR, a large ripple current can result in high total capacitor power loss, especially under fluctuating power conditions. The increase of capacitor power loss causes a higher operating temperature inside the capacitor. The total capacitor power loss and capacitor core temperature T_h can be calculated by using the capacitor ripple current as [17]:

$$P_{\text{loss}} = \sum_{n=1}^{N} I_{f_n}^2 \text{ESR}(f_n) \tag{5}$$

$$T_h = T_a + P_{\text{loss}} R_{\text{th}} \tag{6}$$

where I_{f_n} is capacitor ripple current at frequency f_n and $\text{ESR}(f_n)$ is the value of the ESR at a particular frequency f_n. T_a is the capacitor ambient temperature, and capacitor thermal resistance is R_{th}. Since the capacitor's heating will lead to electrolytic gas escaping through the end seal, the increase of capacitor ripple current and ESR will accelerate the aging process of the capacitor. Thus, the relationship of the electrolyte volume and the ESR can be expressed by [12]:

$$\frac{\text{ESR}}{\text{ESR}_{\text{ini}}} = \left(\frac{V_{\text{ini}}}{V}\right)^2 \tag{7}$$

where ESR_{ini} is the initial ESR (Ω) and V_{ini} is the initial volume of electrolyte (units). If the electrolyte volume is reduced by 40%, the ESR value is increased by factor of

2.8. Under such circumstances, the electrolytic capacitor is considered to be a failure [12]. Therefore, for electrolytic capacitor applications, higher capacitor ripple current will lead to an increased internal heating that in turn accelerates the evaporation of electrolyte and degrades the lifetime.

Through the analysis of a rectifier circuit with filter capacitor subject to supply voltage fluctuations in Section III, the capacitor peak ripple current is increased dramatically along with the rms current value as the flicker modulation frequency increases. Since the ripple current and ambient temperature are the main contributors to the lifetime reduction of the capacitor, it means that the aging process will accelerate under flicker power condition, especially with high flicker modulation frequencies. On the other hand, it should be noted that if using low line impedance sources, the expected life of capacitor will be significantly reduced as well [10].

V. Summary and Future Work

In this paper, an analysis of the singe-phase rectifier with capacitor filter subject to supply voltage fluctuations has been presented. Such a study has been undertaken in order to further understand the electrolytic thermal stress effect on lifetime reduction. The results presented indicate a good correlation between simulation and experiment under different voltage fluctuation conditions. Voltage fluctuations result in the capacitor ripple current increasing dramatically and this phenomenon keeps deteriorating as the fluctuation frequency increases. These ripple currents have the undesirable effects of raising the electrolytic capacitor temperature and accelerating their aging process.

Further research on this subject should develop the electrolytic capacitor heating mechanism under voltage fluctuations with various modulation amplitudes and frequencies. Capacitor lifetime evaluation experiments will be carried out to quantitatively analyse the impact of the rectifier currents on the dc-bus capacitor lifespan when subject to supply voltage fluctuations.

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