Metal Oxide Varistor (MOV) Lifetime Estimation with Impulse-Based Testing in PV Inverter Systems

Preprint

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Metal Oxide Varistor (MOV) Lifetime Estimation with Impulse-Based Testing in PV Inverter Systems

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Abstract—**Surges caused by lightning strikes could damage electrical components in photovoltaic (PV) systems. Metal oxide varistors (MOVs) are commonly used to protect PV systems from lightning strikes. This paper proposes a holistic impulse-based MOV lifetime estimation framework. The impacts of peak current and fault duration induced by lightning events are considered in the MOV lifetime estimation framework. Moreover, the impact of different parameter combinations on MOV lifetime estimation is analyzed. The effectiveness of the proposed work is validated in a PV inverter test system developed in MATLAB/Simulink.**

Keywords—metal oxide varistors (MOVs), photovoltaic (PV) systems, lifetime estimation

I. INTRODUCTION

In recent years, the penetration level of renewable energy resources in modern power systems has increased significantly. Given the sustainability of solar photovoltaic (PV) systems, they have been developed and widely deployed worldwide. A typical PV system comprises PV panels and power electronics converters (e.g., DC-DC converters and DC-AC inverters) [1]. The power generated by the PV system is delivered to the power system through grid-connected inverter interfaces. To maximize the solar energy harvest, PV systems are usually installed in large outdoor locations without the obstruction to realize efficient operation; however, PV systems installed in open areas could be vulnerable to lightning strikes that could cause surges and damage electrical components. Further, the cost-effectiveness of the PV system deployment could be influenced by the potentially high cost of repair or replacement of the damaged components [2], [3].

Metal oxide varistors (MOVs) are commonly employed as surge protective devices (SPDs), such as surge arresters, to reduce the risk of unexpected failure resulting from lightning strikes [4]. Specifically, MOVs are variable resistors that are primarily comprised of zinc oxide (ZnO), which can suppress the transient voltage surges. When MOVs are exposed to high-voltage transients, their resistance can vary from a significantly high value (i.e., the near open circuit) to a very low value, so that the transient overshoot can be bypassed. Further, MOVs can absorb the potentially destructive energy of the incoming transient impulse to protect the electrical equipment. But as the number of surge events increases, MOVs can fail in different forms, such as electrical puncture, thermal cracking, and thermal runaway [5]. Therefore, it is necessary to estimate the MOV lifetime to effectively manage the maintenance plan and reduce the operation-and-maintenance (O&M) costs of PV systems (i.e., to repair or replace MOVs before they fail to ensure MOVs can be functional for PV system protection).

Tremendous efforts have promoted the development of the MOV lifetime estimation model. In [6], the lifetime of MOV-based surge arresters can be extrapolated using the Arrhenius model when the temperature is identified as the major stressor in accelerated aging tests. In [7], through multiple accelerated aging tests, an approach for evaluating the MOV lifetime based on the time-current curve is proposed. In [8], a method to estimate the impulse lifetime of MOVs using the median rank regression (MRR) method based on the Weibull distribution is presented. In [9], by analyzing the different combinations of the sequence in which surges occur, the MOV impulse lifetime is calculated based on the pulse rating curves that highlight the relationship between peak surge current and impulse duration; however, the impulse-based MOV lifetime estimation model applied in PV systems with practical and application-specific considerations (e.g., fault locations, impacts on multistage inverters) have not been sufficiently discussed.

This work proposes a holistic framework of impulse based MOV lifetime estimation used in PV systems. Generally, the impulse based MOV lifetime is defined as the maximum allowable number of impulses before the MOV fails. As shown in Fig. 1, the MOV impulse characteristics can be represented by the pulse rating curves that identify the relationship between the peak surge current and the impulse duration. It is noteworthy that the maximum allowable number of impulses with a given combination of peak fault current and fault current duration is also provided in the cluster of MOV pulse rating curves. In other words, the pulse rating curves provide the estimated MOV lifetime when exposed to multiple impulses (e.g., lightning strikes over years). For instance, the sample point A in Fig. 1 indicates that an impulse with an 80-μs duration can generate an approximate 1-kA peak surge current; thus, the corresponding maximum allowable number of impulses is 2 from Fig. 1, which means when the second such impulse applies on the MOV, it will be damaged. Eventually, the MOV lifetime can be estimated based on the time point when the MOV is damaged. Moreover, the profile collection and the model design of impulses need to be considered in the proposed framework. In order to obtain the

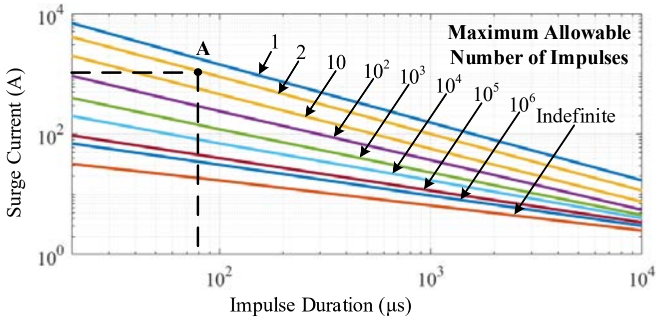

Fig. 1. MOV pulse rating curves.

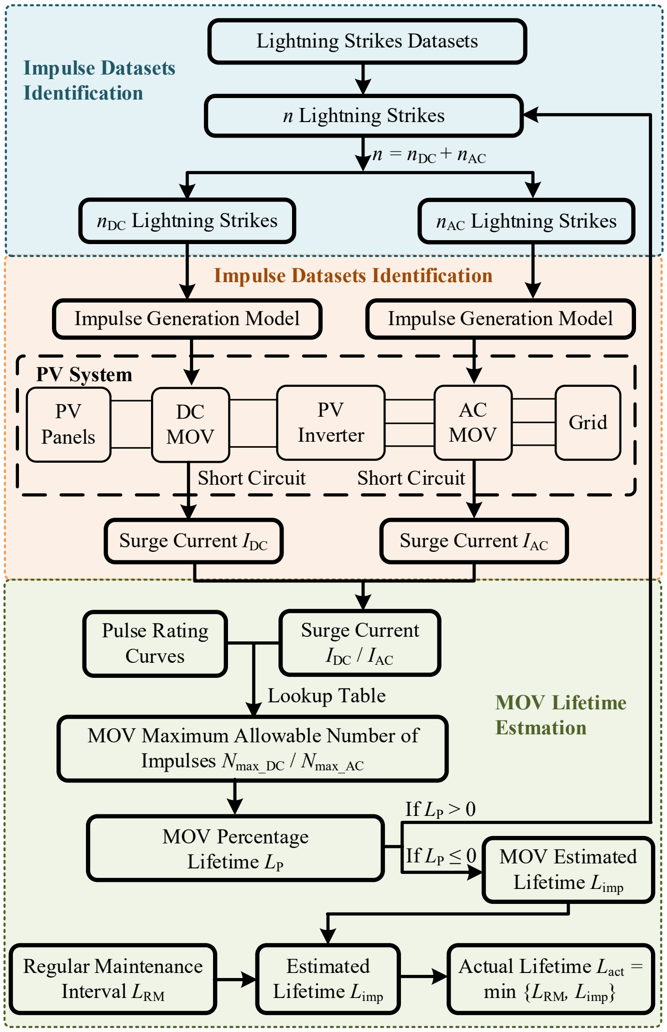

Fig. 2. Flowchart of the proposed framework for the MOV impulse lifetime estimation.

frequency of pulses occurring in a certain area during a certain time period, available impulse data sets are identified. On the other hand, the impulse generation model is established and integrated into the PV system. They will be discussed in Section II in detail.

The remainder of this paper is organized as follows: Section II introduces the proposed holistic framework of the impulse-based MOV lifetime estimation. Section III analyzes the effect of different parameter combinations on MOV lifetime estimation and presents the case study on a test system to verify the proposed solution based on the impulse characteristics of practical MOVs. Section IV summarizes the paper and draws the conclusion.

TABLE I
SAMPLE LIGHTNING STRIKES DATA SETS

Area	Year	Date	Number of Lightning Events n
Tampa, FL	2021	01/01	$n = 0$
		01/02	$n = 0$
		…	…
		02/07	$n = 4$
		02/08	$n = 4$
		…	…
		12/21	$n = 1$
		…	…
		12/31	$n = 0$

II. PROPOSED FRAMEWORK FOR IMPULSE-BASED MOV LIFETIME ESTIMATION

The flowchart of the proposed framework for the impulse based MOV lifetime estimation is depicted in Fig. 2. The whole framework can be divided into three subsections, including impulse data set identification, impulse generation model implementation, and MOV lifetime estimation. The details are introduced as follows.

A. Impulse Data Set Identification

Given that lighting strikes are considered as impulses in this work, lighting strike data sets are collected from reliable data sources, such as an integrated database of severe weather records of the United States provided by the National Centers for Environmental Information (NCEI). The lightning strike data set in a specific area during a certain time period is provided and thereby used as the input variable of the proposed framework [10]. For example, based on the weather records provided by NCEI, Table I shows a sample lighting strike data set for Tampa, FL, during the year 2021. It shows that there is a total of n lightning strikes detected at the identified location, and n could be zero if no lightning strike is detected on that day. In this way, the number of lightning strikes occurring per day and the total number of lightning strikes occurring during a long-time interval (e.g., years) in a specific area can be identified.

Further, for a given PV inverter system, it is assumed that n_{DC} lighting strikes are detected on the DC side of the inverter and n_{AC} lighting strikes are detected on the AC side of the inverter. More importantly, given that the time and location of the lightning strike are uncertain, the n_{DC} and n_{AC} can be arbitrarily selected, and their summation should be equal to the total number of lightning strikes n (i.e., $n = n_{DC} + n_{AC}$).

B. Impulse Generation Model Implementation

By referring to the modeling of the ring wave [11], [12], the impulse generation model can be developed as a voltage-source-based impulse signal, as shown in Fig. 3. Its mathematical expression is given by:

$$V(t) = 1.590 \cdot V_m \cdot (1 - e^{\frac{-t}{0.533e-6}}) \cdot e^{\frac{-t}{9.788e-6}} \cdot \cos(2\pi f \cdot t) \quad (1)$$

where V_m is the magnitude; f = 100Hz is the oscillating frequency; and t is the time.

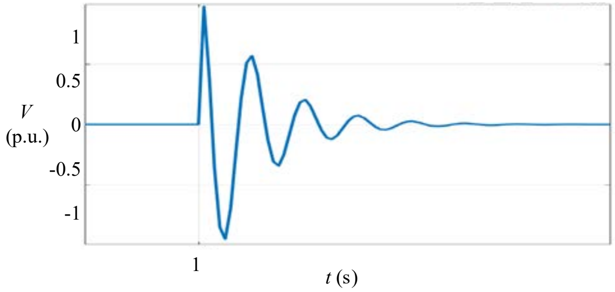

Fig. 3. Impulse generation model.

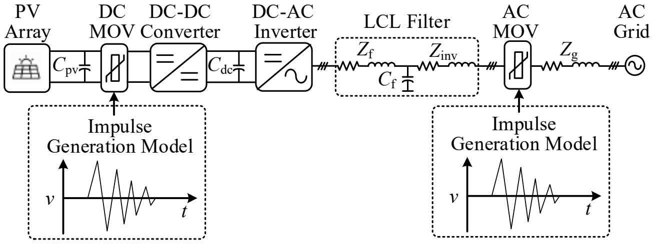

Fig. 4. A test PV system.

Note that it is also assumed that each lightning strike has the same magnitude and duration for simplification. Further, because lightning strikes randomly occur on the DC side or AC side of the inverter, the impulse generation models are implemented on both the DC and AC sides of the inverter; therefore, the short circuit is locally triggered, so the peak surge currents, I_{DC} and I_{AC}, are calculated on both the DC and AC sides of the PV inverter. Additionally, the root-mean-square (RMS) value of the variables is computed to allow reasonable identifications of the oscillatory surge currents produced by the impulse model:

$$i_{\mathrm{RMS}} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left|i_n\right|^2} \tag{2}$$

where N is the number of current measurement data points (impulse duration/sampling time step).

C. MOV Lifetime Estimation

After calculating the peak surge currents, I_{DC} and I_{AC}, the next step is to realize the lookup table between the calculated surge currents and the given pulse rating curves. As a result, for both the DC and AC sides, the MOV maximum allowable numbers of impulses, $N_{\max\_DC}$ and $N_{\max\_AC}$, can be determined, respectively. In other words, $N_{\max\_DC}$ and $N_{\max}$ can be directly read from the pulse rating curves as long as the impulse duration and peak surge current are identified. Note that the values of $N_{\max\_DC}$ and $N_{\max}$ could be significantly different due to different fault current levels (i.e., I_{DC} and I_{AC}).

It is assumed that the MOV initial percentage lifetime is considered as 100%, so the MOV remaining percentage lifetime, L_P, can be thereby computed as:

$$L_{\mathrm{P}} = (1 - L_{\mathrm{lost}}) \cdot 100\% \tag{3a}$$

$$L_{\mathrm{lost}} = \sum_{i=1}^{n_{\mathrm{DC}}} \frac{1}{N_{\max\_\mathrm{DC}\_i}} + \sum_{j=1}^{n_{\mathrm{AC}}} \frac{1}{N_{\max\_\mathrm{AC}\_j}} \tag{3b}$$

TABLE II
DIFFERENT PARAMETER COMBINATIONS AND PRODUCED MAXIMUM PEAK CURRENT

No.	Z_{inv} (Ω)	Z_g (Ω)	Z_{inv} / Z_g	I_{max} (A)
1	0.032	3.878	0.008	296
2	0.064	3.878	0.017	215
3	0.128	3.878	0.033	150
4	0.256	3.878	0.066	110
5	0.513	3.878	0.132	80

TABLE III
SAMPLE LIGHTNING STRIKES DATA SETS IN TAMPA, FL, 2017–2021

Year	The Number of Lightning Strikes	Total
2021	621	4156
2020	391	
2019	493	
2018	1810	
2017	841	

In (3a), $L_P > 0$ means the MOV has not come to the end of life at this point so the calculation of L_p will be repeated based on the upcoming event where lightning strikes are detected, until L_P becomes smaller than 0, which means the MOV is damaged, and the MOV lifetime is estimated based on the current time point.

Finally, a concept of regular maintenance is introduced as a hard limit for the MOV lifetime estimation. For example, the required regular maintenance intervals (e.g., 5 years) may be shortened given the estimated lifetime; therefore, the minimum value between the regular maintenance interval and the estimated MOV lifetime based on the proposed framework should be determined as the MOV final actual lifetime.

III. CASE STUDY

In a typical PV system, the inverter-side impedance, Z_{inv}, is part of the inverter LCL filter, and the grid-side impedance, Z_g, is used to connect the entire system to the external grid. For a given PV system with the identified combination of these two parameters (i.e., the values of Z_{inv} and Z_g), the corresponding MOV lifetime estimation model can be used. In terms of the different parameter combinations, the MOV lifetime can be evaluated accordingly; therefore, it is important to analyze the impacts of different parameter combinations on MOV lifetime estimation. Moreover, the system might fail if the MOV on any one of the three phases runs toward the end of the lifetime, which means only the generated maximum peak current, $I_{max} = \max\{I_{a\_max}, I_{b\_max}, I_{c\_max}\}$, over the three phases is considered because it can lead to the minimum MOV lifetime estimation. Specifically, the relationship between different parameter combinations and the I_{max} produced by lightning events is summarized in Table II. It shows that I_{max} decreases with the increase of Z_{inv}. In this work, the first parameter combination in Table II (i.e., No. 1) is selected as an example to illustrate the following MOV lifetime estimation.

As shown in Fig. 4, to validate the proposed approach, the test grid-connected PV system is established, including PV panels, one DC-DC converter, one DC-AC inverter, and two designed impulse generation models on both the DC and AC sides of the inverter. The corresponding system dynamic responses are shown in Fig. 5. In this case, the lighting strikes detected in Tampa, FL, are selected as the sample data sets.

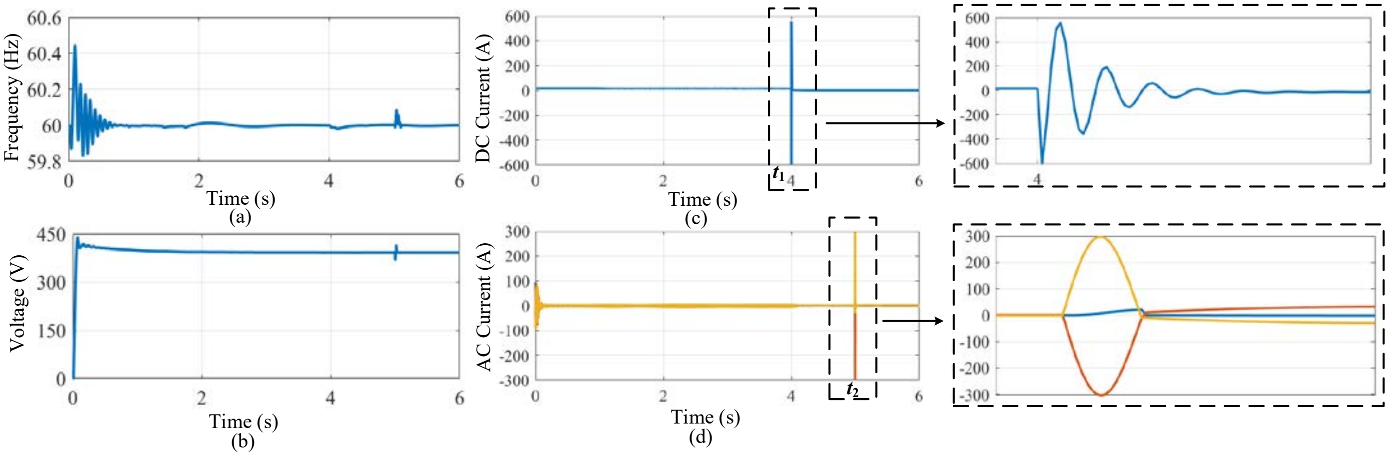

Fig. 5. Simulation dynamic response of (a) frequency, (b) voltage amplitude, (c) DC surge current, and (d) AC surge current.

The number of lightning strikes in recent years (i.e., 2017–2021) are summarized in Table III [10]. Further, the designed impulse generation models are activated, so the short-circuit fault on the DC side is emulated and triggered at $t = t_1$, whereas the short circuit on the AC side is triggered at $t = t_2$. The waveforms of the frequency and voltage amplitude are shown in Fig. 5 (a) and (b), and the measured surge currents, I_{DC} and I_{AC}, are shown in Fig. 5 (c) and (d), respectively. After the comparison between the measured surge currents and the provided pulse rating curves, the MOV maximum allowable numbers of impulses, $N_{max\_DC} = 3000$ and $N_{max\_AC} = 10000$, can be determined. Eventually, it is shown that there are 4,156 lightning strikes occurring in Tampa, FL, during the 5-year window, and the probability of lightning strikes on both the DC and AC sides is 50%; therefore, after 5 years, the MOV has lost approximately 90% lifetime by using (3b), and the estimated MOV lifetime is calculated as 5/90% $\approx$ 5.56 years. Moreover, the required regular maintenance interval could be designed shorter than the estimated lifetime.

IV. CONCLUSION

In this work, to enhance the reliability of MOV applied in PV systems, the impulse based MOV lifetime evaluation model is developed based on the proposed holistic framework. This framework integrates the impacts of peak surge current and fault duration generated by lightning strikes. Further, the wide range of parameter combinations is explored considering the lightning events. Finally, based on the impulse characteristics of practical MOVs, the proposed work is validated through case studies.

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