Investigation of lightning surge effects on a grid-connected PV plant

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***Abstract*—This paper investigates the indirect effects of lightning on a medium-scale photovoltaic plant. The purpose of the investigation is to analyse the surge effects on the photovoltaic plant and interconnected systems in order to develop an understanding of the associated risk of damage to the plant and ascertain the requirements for lightning protection. The investigated plant consists of four photovoltaic arrays, each comprising 2500 modules connected in series-parallel configurations, with inverters and connection to the high voltage transmission grid via a system of parallel buses, insulated power cables and power transformers. The presented study makes use of the electro-magnetic transient program-restructured version (EMTP-RV) software platform to investigate induced effects of lightning on grid-connected PV systems and provide system designers with a means of analysing and mitigating lightning risk. Results obtained show significant risk associated to voltage rise of 7.4% on the DC side and 1.2 p.u on the AC side.**

***Index Terms*—Photovoltaic plant; induced surges; lightning protection; protection; surge arrester.**

I. INTRODUCTION

The proliferation of grid-connected photovoltaic (PV) systems has become a global trend owing to well-known economic and environmental benefits. This widespread implementation of PV systems implores suitable understanding of risks and subsequent application of measures to mitigate such risks. One such risk, which PV systems may be inherently exposed to, is lightning phenomena. Lightning flashes pose significant risk of damage to PV array and interconnected systems via direct and indirect effects [1].

Medium to large-scale PV plants located in areas associated with higher ground flash densities [2], are particularly vulnerable to the effects of lightning as there is no physical shielding to the elements (unobstructed arrays) over larger area/dimensions. Furthermore, the IEC 62305 suite of lightning protection standards [3]-[6] are available for lightning protection for existing structures, environmental and system conditions but do not offer specific guidance for lightning protection on PV systems. The knowledge pertaining to analysis, design and installation of lightning protection for PV installations is still premature [7].

In the presented study, a model of the complete plant, with grid connection, is built in EMTP-RV and analysed under different scenarios of potential lightning incidents. The plant is a medium voltage (MV) photovoltaic plant that feeds into the high voltage (HV) transmission grid. This study establishes the varying propagation of surges due to indirect lightning effects, at different coupling points, thereby affording the design of a suitable surge protection scheme. Details of selection and coordination of the arresters to provide optimal protection against the analysed risk are also given in the paper.

II. METHODOLOGY

A. Plant Description

The investigated PV plant consists of four PV arrays, each comprising 2500 modules connected in series-parallel configurations. Each of the arrays outputs 1 kV DC to a pulse-width modulation (PWM)-based DC/AC converter which yields a 0.3 kV AC supply. The inverter outputs are connected to four 750 kVA 0.3/22 kV power transformers which are connected the HV transmission grid via a system of parallel buses, insulated power cables and a 22/132 kV power transformer. Table I gives details of the components used in the investigated plant.

TABLE I: Description of plant components

Component	Parameter
PV array	C = 1 nF
Inverters	1.4 MW
MV transformers	YgD, $X = 6\%$
XLPE Cables	R = 0.1 Ω/km, X = 0.094 Ω/km, C = 0.367 μF
HV transformer	YgD, $X = 11\%$
Grid connection	650 kW, 800 kVAr

B. Modelling of Lightning Effects

Typically, the PV array is considered to be the most vulnerable equipment to direct lightning and therefore forms the focus of lightning protection studies [8]. However, the indirect effects of lightning are more frequent phenomenon than direct lightning [9], and induced overvoltages through factors inter alia cabling [10], positioning of cables with respect to PV array [7], and inverter configuration [2], pose significant risk and also need to be considered.

For the present investigation, indirect effects of lightning are considered. Specific points on the PV plant are selected for attachment of induced effects of lightning:

1) At the DC-side of the plant inverter.

2) Between inverter and 0.3/22 kV power transformer, on the AC-side of the plant.

The plant under study is built up on the EMTP-RV software platform. Lightning strikes are modelled using the ICIGRE lightning current source tool of the EMTP-RV 3.3 simulation package. This tool is capable to provide the current shape of lightning stroke used for performance analysis of equipment under lightning phenomena. The first current waveform of lightning strokes such as modelled in the ICIGRE lightning current source consisted of a combination of the front and tail wave equations:

The front wave equation is given as follows:

$$I = At + Bt^n \tag{1}$$

$$A = \frac{1}{n-1}\left(0.9n \cdot \frac{I_{max}}{t_n} - S_m\right) \tag{2}$$

$$B = \frac{1}{t^n\,(n-1)}\left(S_m t_n - 0.9 I_{max}\right) \tag{3}$$

$$n = 1 + 2\left(S_N - 1\right) \cdot \left(2 + \frac{1}{S_N}\right) \tag{4}$$

$$t_n = 0.6 t_f \left[\frac{3(S_N)^2}{1+(S_N)^2}\right] \tag{5}$$

$$S_N = S_m \cdot \frac{t_f}{I_{max}} \tag{6}$$

The tail wave equation is given as follows:

$$I = I_1 \cdot \exp - \frac{(t-t_n)}{t_1} - I_2 \cdot \exp - \frac{(t-t_n)}{t_2} \tag{7}$$

$$t_1 = \frac{t_h - t_n}{\ln 2} \tag{8}$$

$$t_2 = 0.1 \cdot \frac{I_{max}}{S_m} \tag{9}$$

$$I_1 = \frac{t_1 \cdot t_2}{t_1 - t_2}\left(S_m + 0.9 \cdot \frac{I_{max}}{t_2}\right) \tag{10}$$

$$I_2 = \frac{t_1 \cdot t_2}{t_1 - t_2}\left(S_m + 0.9 \cdot \frac{I_{max}}{t_1}\right) \tag{11}$$

Where:

I	:	front wave current equation.
t_n	:	time to reach 90% of amplitude.
t_f	:	front time.
t_h	:	time to half value.
I_{max}	:	amplitude of the current wave.
S_m	:	maximum steepness.

For the purpose of indirect effects of lightning surge current, it is considered that lightning has struck a nearby object. As a result of magnetic coupling between the struck object and the plant earthing electrode, lightning surges have entered and made their way to the inverter/transformer section of the PV plant. The coupling circuit was represented by a resistance of 22 ohms and an inductance of 4 μH [11]. The coupling between DC side of the inverter was indicated using an 0.1 nF. The lightning surge current such as used in this study consisted of a 10/50 μs 100 kA amplitude with 150 kA/μs maximum steepness. The risk associated to this phenomenon could be effectively mitigated by the use of surge arresters.

III. Results and Discussion

EMTP-RV simulation runs of induced effects of lightning surges show significant risk of overvoltages on both DC and AC sides of the inverters. Upon a lightning strike on a nearby object, the DC voltage on the inverter suddenly rises to a peak value of 1.074 kV which represents 7.4% voltage rise. The lightning impulse current such as applied to this study is shown in Fig.1, and the inverter DC voltage rise experienced is indicated in Fig.2. On the AC side of the inverters, voltage rise to a peak magnitude of 0.684 kV, which corresponds to 1.28 p.u rise, was obtained.

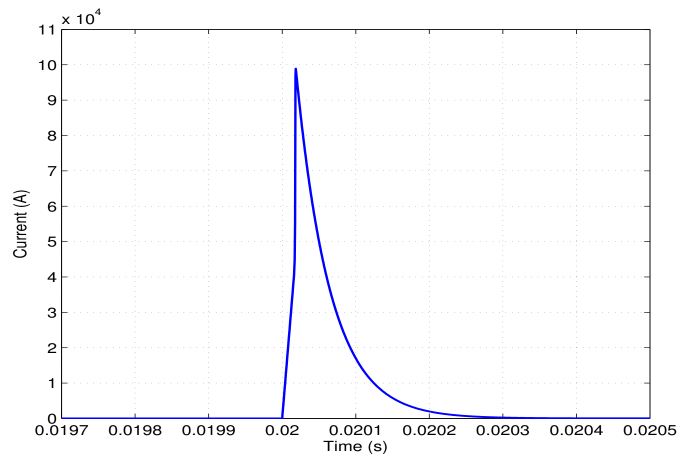

Figure 1: Lightning current surge

In both cases of voltage rises experienced, the risk of damage to the inverter control circuits as well as to transformer insulation cannot be ignored. This could ripple up to financial implications that may result from production losses or plant downtime. However, this potential risk could be mitigated using correct placement of surge arresters and proper earthing electrode. Surge arresters will clamp induced voltages to a safe level, while diverting surge currents to earth. This mitigation technique, although successful for the inverter/transformer AC voltage, does not appear to offer protection to the DC input terminals of the inverters. The voltage waveforms obtained, owing to an arrester being connected to the designated entry point of lightning, are shown in Fig.3 and Fig.4.

However, effective mitigation could therefore be achieved by connecting surge arresters across the input terminals of

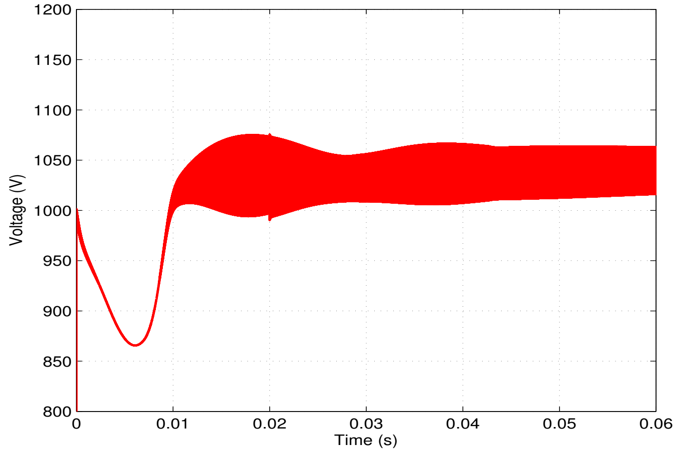

Figure 2: Inverter DC Voltage rise

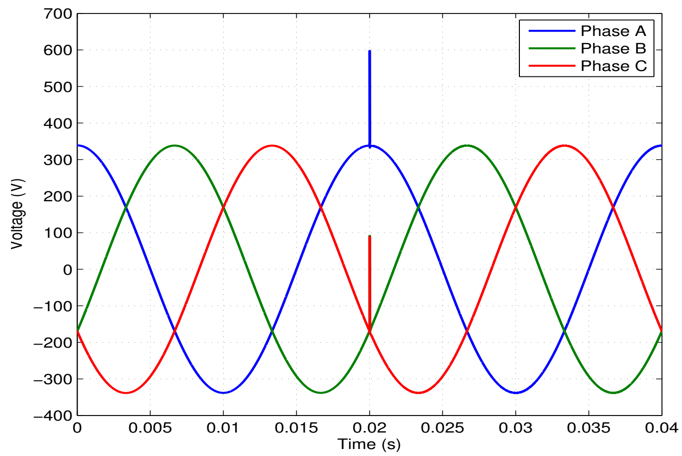

Figure 3: Inverter/Transformer AC Voltage rise

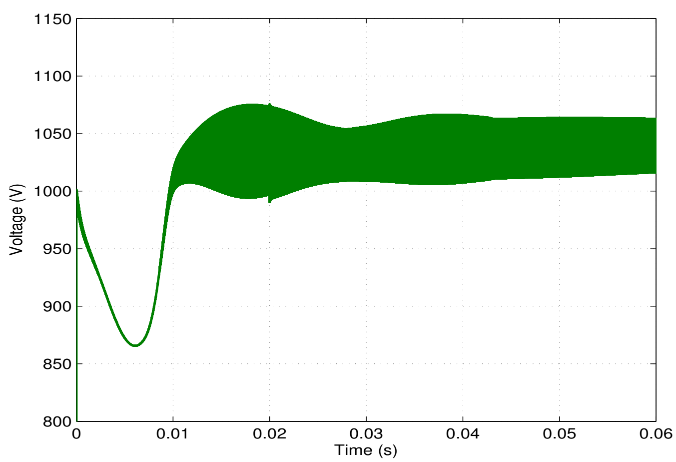

Figure 4: DC Voltage with arrester connected

inverters in such a way that they may be coordinated with the entry point arrester. This arrangement provides the optimum protection against induced effects of lightning such as investigated in this study. Fig.5 shows reduction of the amplitude DC voltage to 0.997 kV. Fig.6 depicts inverter/transformer voltages with an arrester being connected. Fig.7 and Fig.8 indicate the plant model before and after protection against induced effects of lightning.

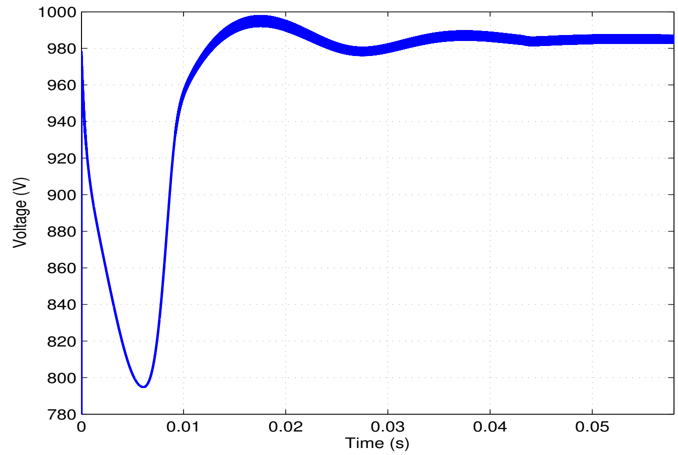

Figure 5: DC Voltage with arrester across inverter input terminals

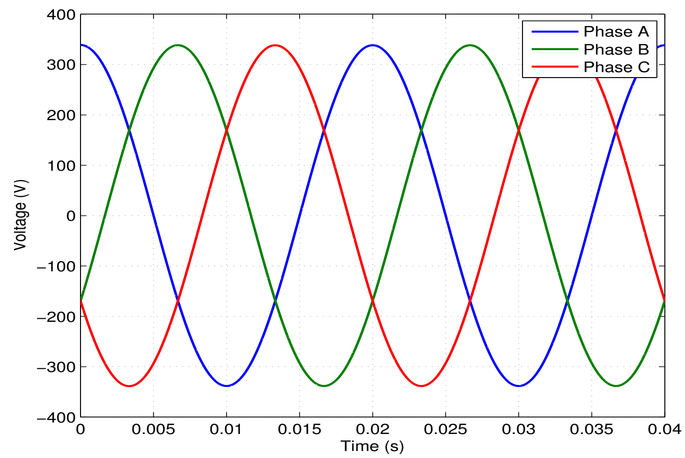

Figure 6: AC Voltage with arrester connected

IV. Conclusion

Induced effects of lightning are quite common phenomena affecting PV solar plants in South Africa. Risks associated to this event have proven to be significant, and may affect both DC and AC sides of the plant. This study shows that effective mitigation of induced transients, originating from lightning strikes on a nearby object, can be achieved by coordinating surge arresters on the DC side with the main entry point arrester. This arrangement may provide the most reasonable and cost-effective lightning protection to PV solar plant.

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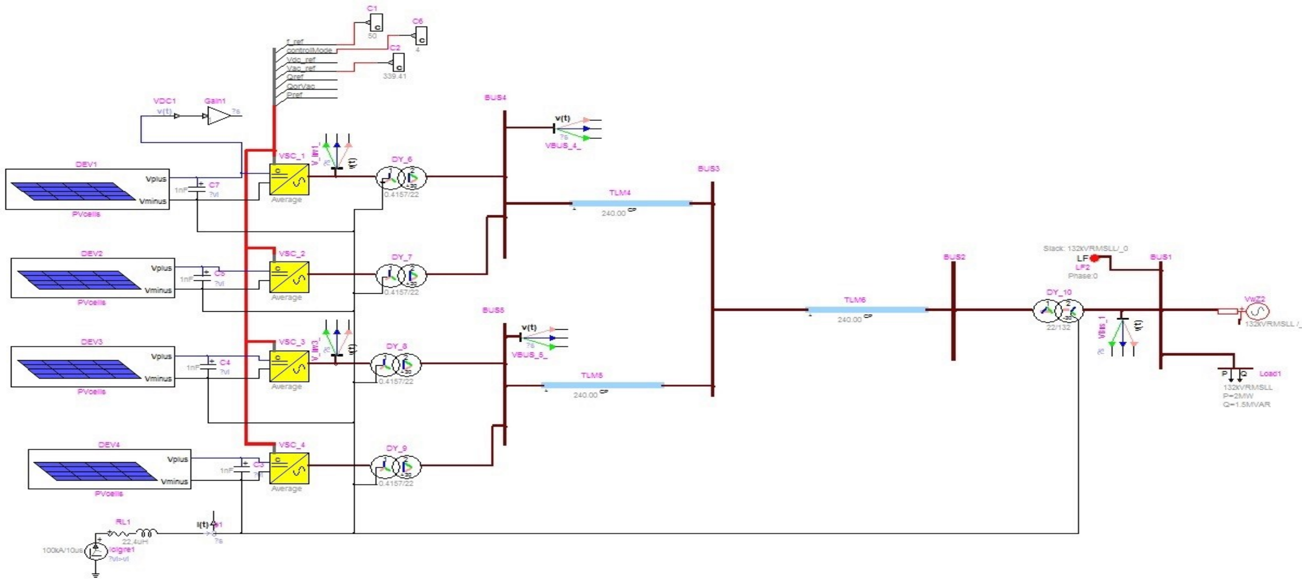

Figure 7: PV Plant Model under induced effects of lightning surge

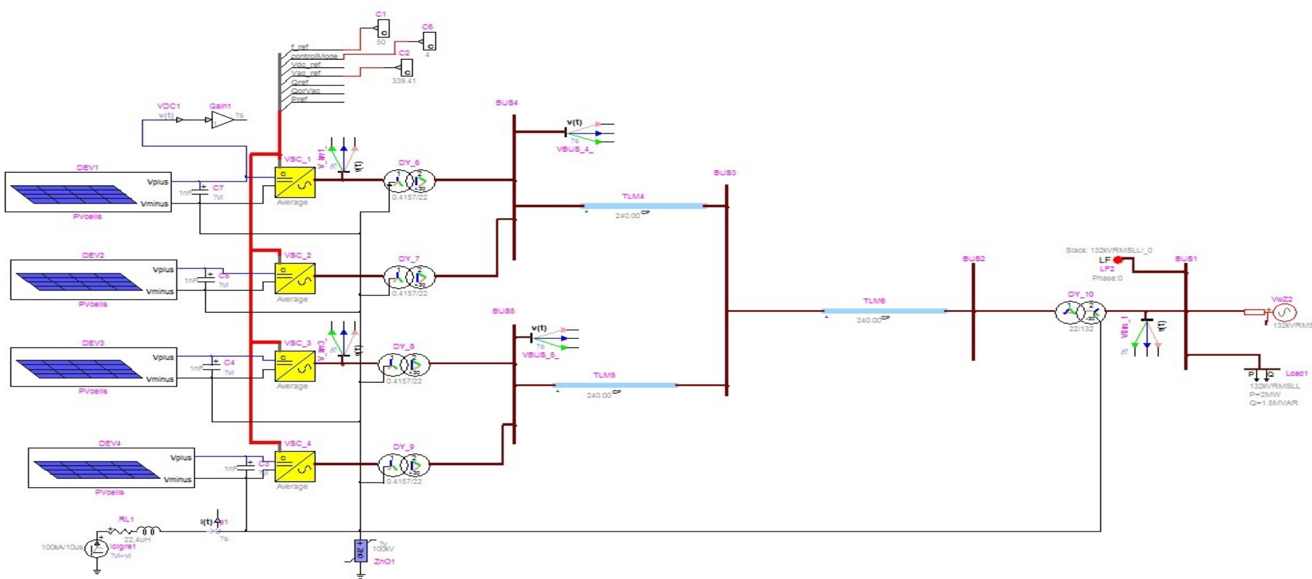

Figure 8: Protected PV Plant Model (induced effects)

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