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# Modelling and validation of arc-fault currents under resistive and inductive loads

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***Abstract* - Over half of all electrical fires in installations are caused by arcing due to poorly connected equipment or wiring system failures. Therefore, it is essential to detect arcs and interrupt them using a suitable protective device. This paper provides a modelling simulation and experimental approach to obtain arc voltage and current. The parameters for the theoretical model were turned based on the experimental results. A realistic case study was done to obtain the arc current under parallel and series arcs. As seen from the results, a parallel arc creates a current much higher than the load current, whereas a series arc current is often lower than the load current. Even though a parallel arc current may be detected by an overcurrent device, as it is often intermittent, it may not sustain to be captured by existing protection devices. Therefore, both parallel and series arc detection and interruption demand a reliable protection device.**

***Keywords - arc current generator, - arc fault, arc detection***

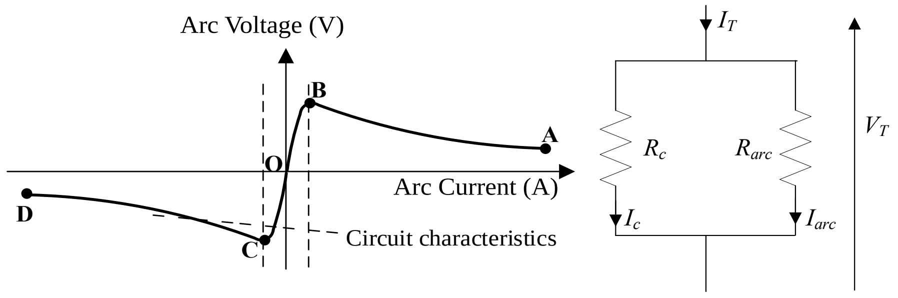
## I. INTRODUCTION

Arc-flash incidents occur every day in many electrical installations. Arcs are visible plasma discharges caused by electrical current passing through a normally non-conductive medium, such as air. This is caused when the electrical current ionizes gases in the air. Fault arc is often followed by the partial evaporation of conductor material. Such an action in the conductor could cause an inflammation in the insulation and as a result, could lead to a fire. The most common causes of arcs are known to be worn contacts in electrical equipment, damage to insulation, kinks in a cable, cable damage caused by drilling or building work, loose-bolted connections, and defective wall plugs. It can also be generated by dropping tools, opening panels on damaged equipment, inserting or removing components from an electrified system, or even a rodent infestation. Although the conventional circuit breaker gives protection from overcurrent and Earth leakage current, they are not effective in protecting from dangerous arcs. The Arc Fault Circuit Interrupter (AFCI) is designed to analyse noise in the current signal, typically at 100 kHz to respond fast enough to detect and break the circuit before causing a fire. To design an effective AFCI, it is important to model the arc current and voltage under many different operational possibilities and then use signal processing techniques to gather the signature of the arc current and voltage.

In the literature, many techniques are reported for obtaining and analyzing arc signals. SeJi, Kim, and Kil [1] have implemented the phase analyses of series arc signals for low-voltage electrical devices such as heaters, computers, refrigerators, and air conditioners. The arc generator has been fabricated according to the UL6199 standard [2]. The phase of detected series arc signals has been analyzed according to load types and finally, a new algorithm was proposed based on the result of phase-resolved series arc analysis to identify types of loads. Taufik, Aarstad, and Kean [3] have presented the development of AFCI lab setup to characterize dc arc current in dc circuits operating at 24-80 V. Different scenarios for dc arcing occurrences in the development of the lab test setup have been explained. Several test results using the developed test setup have been presented to show the characteristics of the arc current. By inspecting the frequency spectrum of arc current, a unique signature of the dc arc was identified. Andrea, Besdel, Zirn, and Bournat [4] present a mathematical model based on circuit components to describe the behavior of the electric arc in static and dynamic situations. Simulation results and experimental results are given for common arc ignition cases. Mahajan, Patil, and Shembekar [5] discussed the modelling and simulation of the arc phenomenon using the Mayr arc model. Ghezzi and Balestrero [6] discuss different Black box, arc models. Simulations and experimental results are compared under different arcing cases. The parameter estimation for different models is also presented. Even though these studies present modelling and model validation under different arcing characteristics (voltage, phase, V-I), none of them provides a comparison of arcing current with the load current under different loading conditions. Therefore, in this paper, an attempt was made to make a comparison between the arcing current and load currents under real-world scenarios.

## II. MODELING APPROACH

Static characteristic of an arc is shown in Figure 1. A to B is a discharge phase and the discharge can be called corona discharge. The arc is extinguished at O and in the second phase, the voltage is reversed. When the reverse voltage reaches the restrike voltage (at C), the discharge re-initiate. Two resistances can be identified: the resistance of the arc ignition time, $R_c$, and the resistance when arc discharge, $R_{arc}$. Many references [7,8,9] are providing "Black box" models that describe an arc by a simple mathematical equation and give the relation between measurable parameters such as arc voltage and arc current. Such an equation is given in equation (1) [4] and it is used for modelling the arc in this paper.




a) Static characteristic b) Equivalent circuit

Fig.1. Static characteristic and equivalent circuit of an arc

$$V_{arc} = \frac{\alpha}{\arctan(\beta I_{arc})} \quad (1)$$

Where, $\alpha$ is a linear function of the arc length and $\beta$ is a fit parameter depending on the material of the electrode.

With the relationship, $V_{arc} = I_{arc}R_{arc}$ and from (1), $R_{arc}$ can be found as:

$$R_{arc} = \frac{\alpha}{\arctan(\beta I_{arc})I_{arc}} \quad (2)$$

The equivalent circuit to represent the static characteristic is shown in Figure 1(b). When the arc current is low, i.e from B to C, from equation (2), the arc resistance, $R_{arc}$, is high and the parallel combination is more or less equal to $R_c$. During the period A to B and C to D, since the current passing through $R_c$ is negligible when compared to $I_{arc}$ the parallel combination can be reduced to $R_{arc}$ only.

Therefore, the overall discharge resistance $R_T$, i.e.

$R_T = \frac{R_c\ R_{Arc}}{R_c\ +R_{Arc}}$ was found by substituting from (2) as

$$R_T = \frac{\alpha R_c}{\arctan(\beta I_{arc})I_{arc}R_c\ +\alpha} \quad (3)$$

Then from Ohm's law

$$V_T = \frac{\alpha R_c\ I_T}{\arctan(\beta I_{arc})I_{arc}R_c\ +\alpha} \quad (4)$$

Due to the arc resistance $R_{arc}$ is considerably low in comparison to the resistance $R_c$, $I_{arc} \gg I_c$ and $I_T \approx I_{arc}$. Therefore, equation (4) was replaced by

$$V_T = \frac{\alpha R_c\ I_T}{\arctan(\beta I_T)I_T R_c\ +\alpha} \quad (5)$$

With a function $F$ that describes the static discharge, equation (5) was written as

$$V_T = F(I_T)$$

For an R-L circuit when an arc occurs in series, the circuit equation was written as:

$$V_g(t) = RI_T(t) + L\frac{dI_T(t)}{dt} + V_T$$

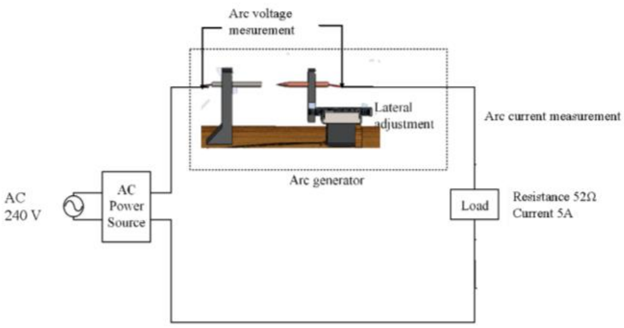
$$= RI_T(t) + L\frac{dI_T(t)}{dt} + F(I_T(t)) \quad (6)$$

The load equation defined by the first two terms of equation (6) may cross the static characteristic in one, two or three points (example case is shown in Figure 1(a)). When solving for the current, one of the possible cross points as the solution was obtained using the least efforts principle [4]. The differential equation of $I_T(t)$ was solved using MATLAB to obtain time plots of arc voltage and current under different loading conditions.

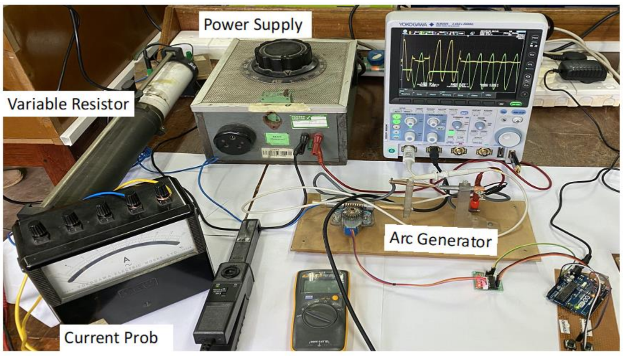
In this experiment, only the series arc was modelled because it is the one type of arc that is not interrupted by existing protection devices as the arc current flowing in the circuit is not higher than the load current while it is also being limited by the load connected in series. In contrast, a parallel arc occurs between conductors within different phases such as line to neutral or line to ground. Since the parallel arc current is higher than load current, it can be detected without any advanced techniques. Corresponding graphs are shown in the results section.

## III. ARC GENERATOR

An arc generator was designed in compliance with the standards BS EN 62606:2013+A1:2017 [2] with an apparatus consisting of a stationary electrode and a moving electrode. One electrode was made using a 6mm ± 0.5 mm diameter carbon-graphite rod and the other electrode was a copper rod as shown in figure 2. The arcing end of one carbon electrode was pointed. The distance between the two electrodes was adjusted by controlling a stepper motor. An Arduino-based controller was designed for this purpose. The arcing current was sensed by a current probe whereas arcing voltage was directly probed by the oscilloscope. Figure 2(a) shows the schematic with the circuit connections and Figure 2(b) shows the laboratory setup used.




(a) Schematic diagram




(b) Laboratory setup

Fig. 2: Arc generator

## IV. Parameter Estimation of the Model

A MATLAB model for simulation of an electric Arc in a circuit was developed as per the theoretical model discussed in the previous section. According to [4], $\alpha$ = 49.0874, $\beta$ = 1.4614, and $R_c$ = 2221Ω were chosen as model parameters. These parameters were chosen by a curve fitting method and the reference does not provide any information about the experimental setup. To make the model compatible with the experimental study, the above parameters were manually tuned and found to be $\alpha$ = 6, $\beta$ = 0.15, and $R_c$= 55Ω.

The external resistance of the experimental setup was approximately 40Ω and inductance was chosen as 10μH. These values were used in the model.

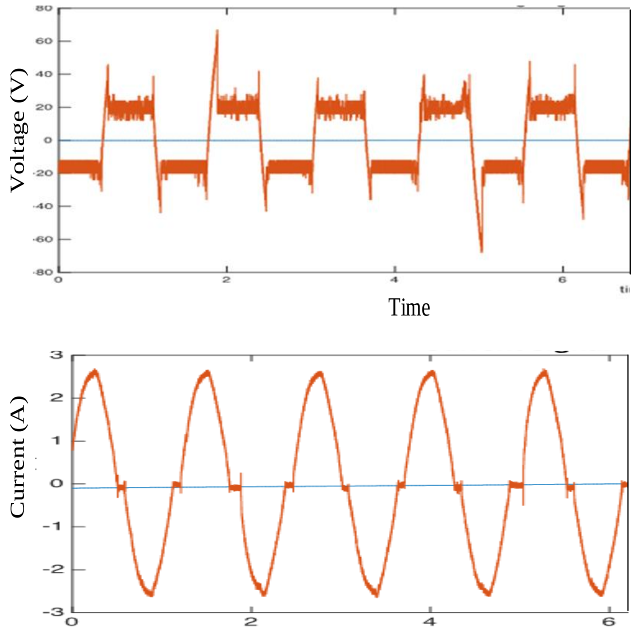



Fig. 3. Simulated arc voltage (top) and current (bottom) (R=40 Ohm, L=10 μH)

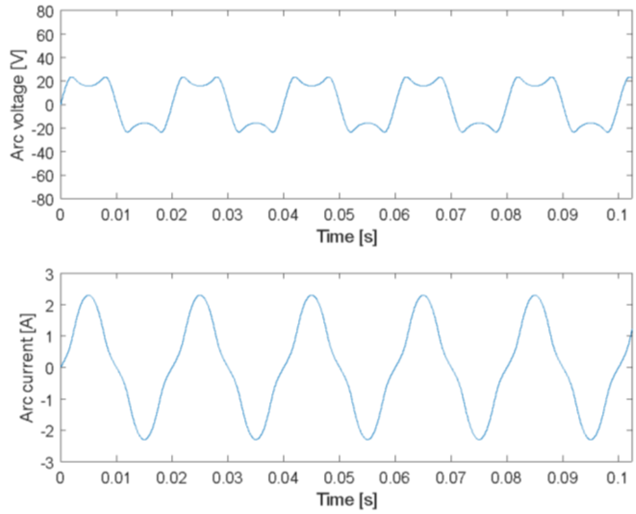



Fig. 4. Experimentally obtained arc voltage (top) and current (bottom)

## V. Case Study

Fig. 5 shows the connection from the distribution transformer to a house and a plug socket within the house. Data of different cable sections are given in Table I.

TABLE I. Parameters of the Cable and Transformer

| | Resistance (Ω/km) | Reactance (Ω) |
|---|---|---|
| Transformer leakage reactance | Negligible | 0.1 |
| Fly conductor | 0.47 | 0.27 |
| Service cable | 1.83 | Negligible |
| Live wire | 13.6 | Negligible |

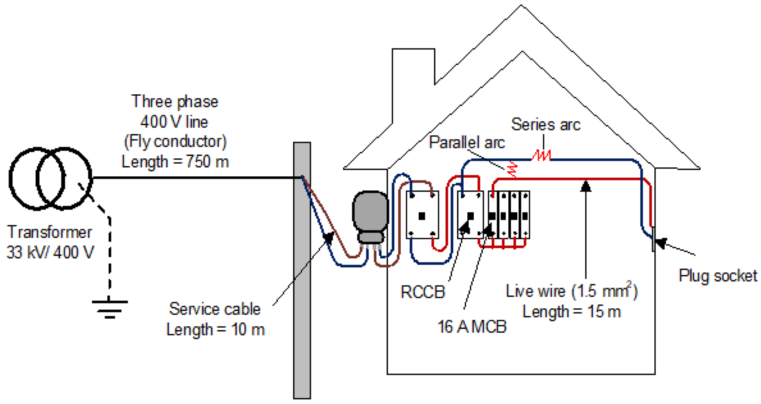



Fig. 5. Sample house for case study

An arc has been formed due to damage to a cable between the live and neutral wires (parallel arc) or due to a loose connection in series with the live wire (series arc).

Fig. 6 and Fig. 7 show the load current and the current when a series arc prevails in the circuit for a 2 kW kettle (a resistive load) and a 2 kW microwave oven (an inductive load) respectively. These appliances are connected to the plug socket shown and it was assumed that the voltage at the transformer is 230 V. As can be seen when the arc is initiated, the current drops from the normal current.

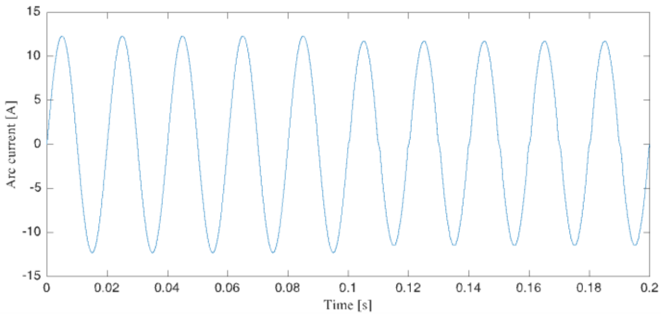



Fig. 6. Arc current when a series arc prevails in the circuit for a 2 kW kettle

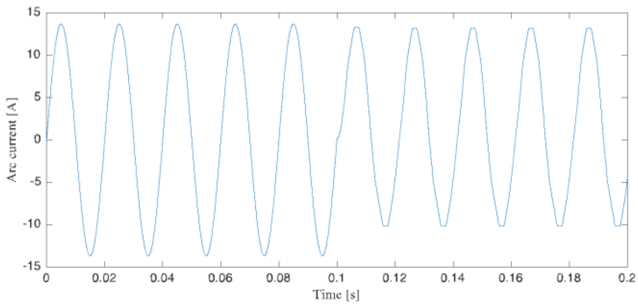



Fig. 7. Arc current when a series arc prevails in the circuit for a 2 kW microwave Oven

Fig. 8 and Fig. 9 show the load current and the current when a parallel arc prevails in the circuit for a 2 kW kettle and a 2 kW microwave oven respectively.

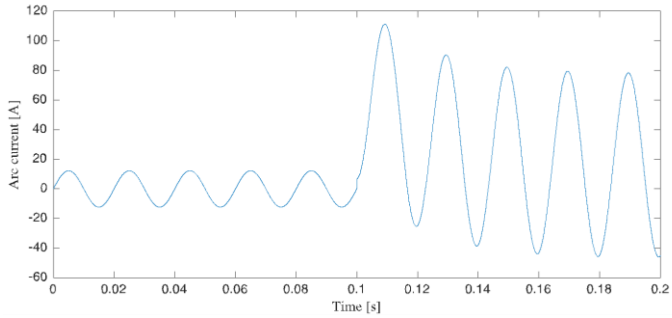



Fig. 8. Arc current when a parallel arc prevails in the circuit for a 2kW kettle

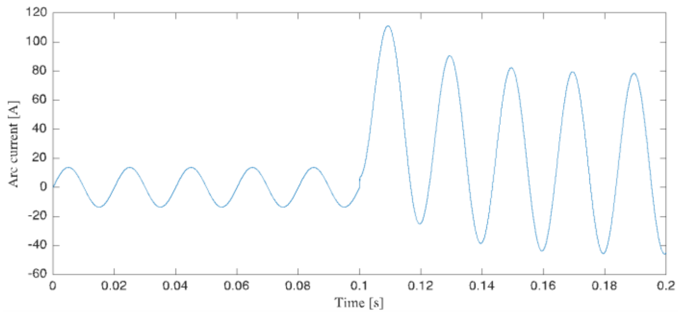



Fig. 9. Arc current when a parallel arc prevails in the circuit for a 2 kW microwave Oven

## VI. Conclusion

Arc currents can be originated in electrical installations due to many reasons. A sustained arc can damage the installation and even lead to a fire. As shown in this paper, an arc current created between the live and neutral conductors (a parallel arc) results in a large current excursion, whereas a series arc created by a loose connection results in a current lower than the load current. Even under a parallel arc, the arcing may be intermittent and therefore will not be detected by an over-current or surge protective devices installed in a premise. Therefore, a specially designed protective device should be connected to installations to detect arc and prevent any adverse circumstances.

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