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Mitigation of Inrush Current and Voltage Drop at Solar Farm Interconnections due to Transformer Energization using Closing Resistors

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SUMMARY

The inrush currents generated during the energization of power transformers connecting a Distributed Energy Resource to the grid are causing significant voltage sags, especially when the transformer is connected to a weak system. The inrush current and resulting step voltage drop can be significantly reduced by using a switching device equipped with a closing resistor. This allows for increased switching frequency and the switching of larger transformers. This paper presents the results of a PSCAD study to confirm that the transformer inrush current is significantly reduced by an optimal closing resistor with a sufficiently long insertion time. The study was performed based on a system with 30 MVA source transformer and a 10 MVA transformer connecting the DER to the distribution system. Comparisons have been made between the effectiveness of pre-insertion time and resistor sizes.

KEYWORDS

renewable, transients, interconnection, transformer inrush, solar farm, voltage drop, voltage fluctuation

I. Introduction

Increased penetration of Solar Farms and other Distributed Energy Resources (DERs) has brought issues with switching the transformers connecting these DERs to existing power grids to the forefront. The inrush current associated with energizing the transformer is not a new issue, but DER applications, like solar farms, are often located on weak parts of the system and the switching frequency can be relatively high. Energizing a transformer connecting a DER to a weak electric system can cause a step voltage drop outside utility defined limits (typically 3 to 5%). DER interconnecting transformers are switched more frequently than similar utility transformers. The DER must be disconnected from the system to avoid islanding during supply interruptions and solar farms may be de-energized at night to avoid transformer no-load losses. The magnitude and frequency of occurrence of the step voltage drop from the DER transformer energization have become a significant problem for electric utilities committed to providing suitable power quality.

If the transformer core is driven into saturation when the transformer is energized, a unidirectional inrush current rich in harmonics is generated. The magnitude of the inrush current, which may approach rated short circuit current of the transformer, is dependent on:

1. Switching point on the voltage wave
2. Magnitude and polarity of any residual flux in the transformer core
3. Source impedance
4. Size of the transformer
5. Magnetic properties of the core
6. Primary winding impedance

To minimize core material, transformers are designed to operate near the knee point of the core B-H curve so a relatively small increase in the core flux over the normal maximum can drive the core into saturation. Due to the shape of the core magnetic hysteresis curve, when a transformer is deenergized, a residual flux will remain on the core. The worst case inrush occurs when there is a residual flux on the core and the transformer is energized at a zero voltage crossing that increases the core flux in the same polarity of the residual flux. In this case, the flux in the core can be well above twice the normal maximum forcing the core deep into saturation. Once this happens, the primary impedance of the transformer is reduced to its air-core value resulting in a very high inrush current. This high inrush current being pushed through the system impedance causes a step drop in the system voltage. On weak systems, the high inrush current can result in a very large step voltage drop and may cause problems.

Historical energization methods using disconnect switches, which energize at voltage peaks, do not take into account the residual flux in the core and can allow inrush currents as much as 10 times the normal load current. As a result, many other strategies have been proposed and applied with varying levels of effectiveness. One method is the use of an independent pole operated (IPO) switching device with a point-on-wave control that calculates and compensates for the residual flux in the core in an attempt to energize the transformer at the precise point on the voltage wave to minimize the saturation of the core and the resulting inrush current. Another method also uses an IPO switching device with a point-on-wave control but with additional equipment to de-flux the core after the previous transformer de-energization. Theoretically, the point-on-wave methods with the residual flux calculation or the de-fluxing of the core work, but the approach discussed in this paper is simple to implement, reliable, and relatively low in cost.

As noted above, one of the variables that determines the magnitude of the inrush current is the primary winding impedance of the transformer. Thus, the proposed solution is to effectively increase the primary winding impedance with a resistor temporarily inserted into the circuit. The resistor size and the insertion time will be selected to limit the inrush current, and the associated step voltage drop, to acceptable limits. The resistor is bypassed when the inrush has sufficiently decayed. This approach

does not require an IPO switching device, a point-on-wave controller, information of residual flux magnitude and polarity, or a de-fluxing of the core to be effective. A simple 3-phase, gang-operated device, with a closing resistor and a random close command, can be utilized for any magnitude and polarity of residual flux or any point on the voltage waveform to effectively limit current and minimize the step voltage drop.

To evaluate the closing resistor technique, a model of a 12.47 kV radial distribution system fed by a 30 MVA transformer with a solar farm connected near the end of the feeder through a 12.47/0.6 kV transformer with the parameters listed in Table 1 was developed in PSCAD.

Rated Power (MVA)	10
Rated Voltage (kV)	12.47/0.6
Impedance (%)	6
Knee Voltage (pu)	1.27
Air-core Reactance (pu)	0.105
Leakage Reactance (pu)	0.0525

Table 1
Transformer Parameters

II. Simulations

a. No Inrush Control, Energization with No Residual Flux

In this case, no residual flux from the previous de-energization was assumed. In order to simulate the worst case for phase A, all three phases were energized simultaneously with phase A energizing at zero voltage. Figures 1 and 2 show the resulting inrush currents and voltages measured on the primary side of the transformer, respectively and Figure 3 shows the rms voltage dip on phase A.

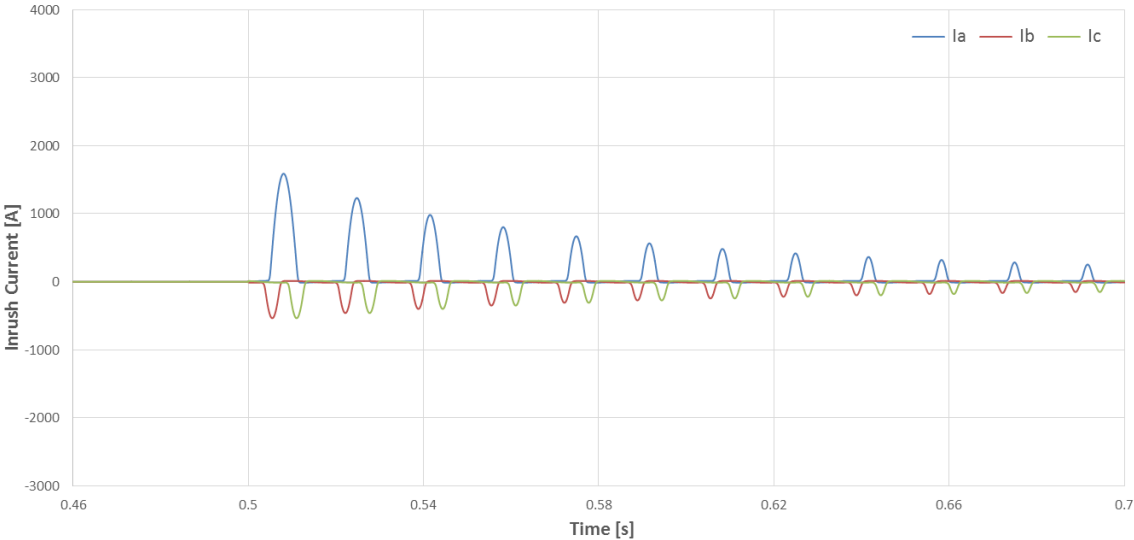


Figure 1
Transformer Inrush Current with No Residual flux

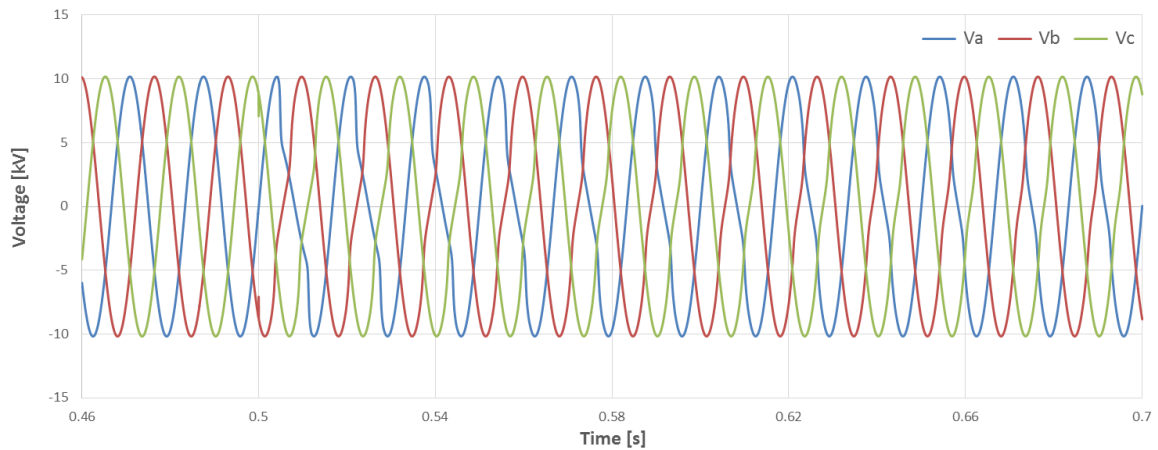


Figure 2
Transformer Primary Voltage with No Residual flux

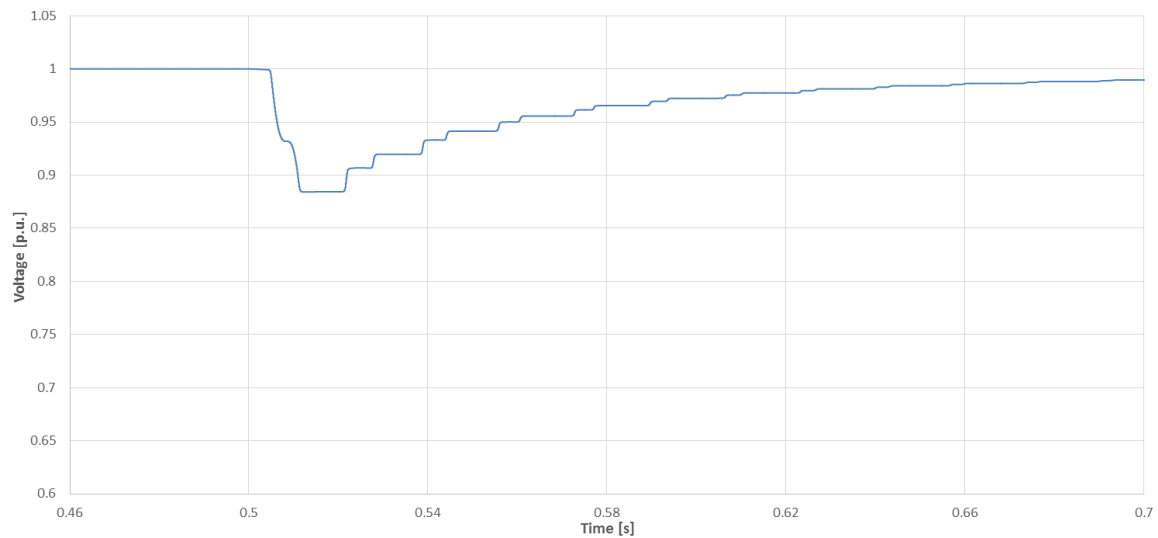


Figure 3
Transformer Primary Voltage, Phase A, with No Residual flux

The inrush current in phase A increased to 1.6 kA peak within the 1st cycle after energization and the voltage on the primary side dropped to 0.88 pu. With most utilities limiting step voltage changes to between 3%-5%, this is not acceptable. It was also noticed that the step voltage drop on other two phases were not as severe as phase A due to the different point on voltage waveform at the instant of energization.

b. No Inrush Control, Energization with Max. Residual Flux

In this case, to obtain an accurate reflection of an energization in the field, a residual flux from the previous de-energization was assumed. The magnitude and polarity of the residual flux are depended on the instant of the previous de-energization of the transformer and are not easy to estimate or measure; however, it is common practice to assume a maximum of +0.8 pu, 0 pu, and -0.8 pu residual flux on phases A, B, and C, respectively. Again, all three phases were energized simultaneously with phase A energizing at zero voltage to give the worst case for phase A. Figures 4 and 5 show the resulting inrush currents and voltages measured on the primary side of the transformer, respectively and Figure 6 shows the rms voltage dip on phase A.

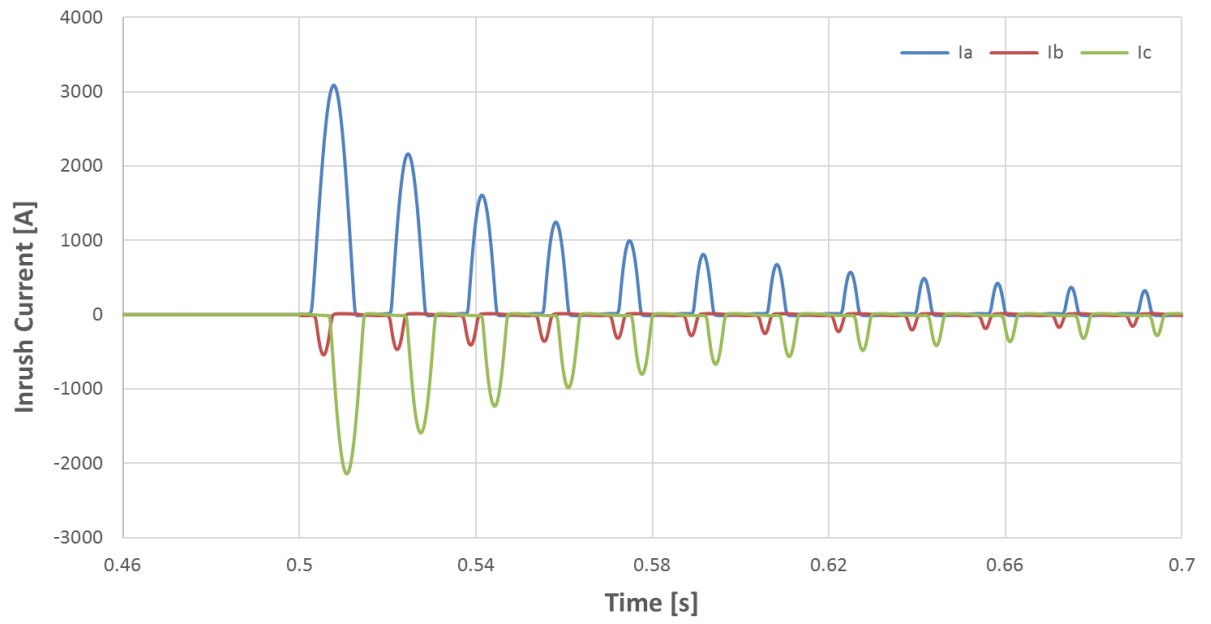


Figure 4
Transformer Inrush Current with Residual flux

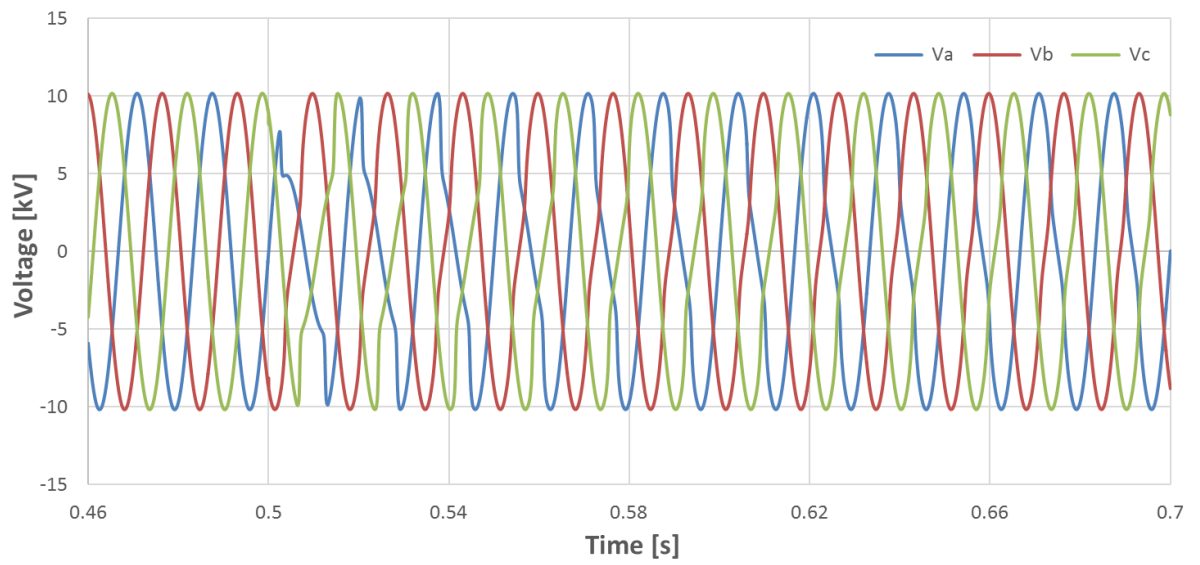


Figure 5
Transformer Primary Voltage with Residual flux

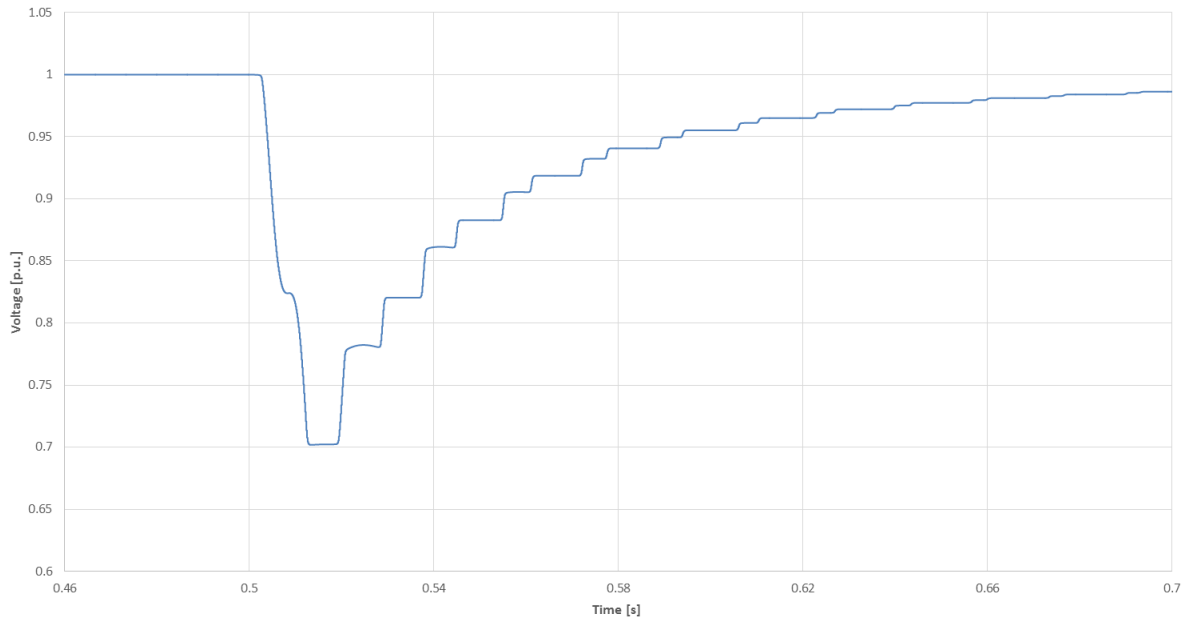


Figure 6
Transformer Primary Voltage, Phase A, with Residual flux

The inrush current in phase A increased to 3.1 kA peak within the 1st cycle after energization and the voltage on the primary side dropped to 0.7 pu. The residual flux on phase A resulted in a deeper saturation of the core and a larger inrush current and voltage drop.

c. Inrush control using Closing Resistor

For this case, various resistor sizes and insertion times were investigated to find the optimal performance for this particular system and maximum residual flux was assumed as in the previous case to present a worst case scenario. It was expected that the duration the resistor is in the circuit largely determines the performance of the inrush mitigation. To investigate this, a study was performed assuming +0.8 pu, 0 pu, and -0.8 pu residual flux on phase A, B, and C, respectively. Again, all three phases were energized simultaneously with phase A energizing at zero voltage to give the worst case for phase A. An 8 ms and a 12 ms insertion time was simulated along a range in closing resistance values. Figure 7 shows the results and indicates that a 50 Ohm resistor with a 12 ms insertion performed best in reducing the inrush current.

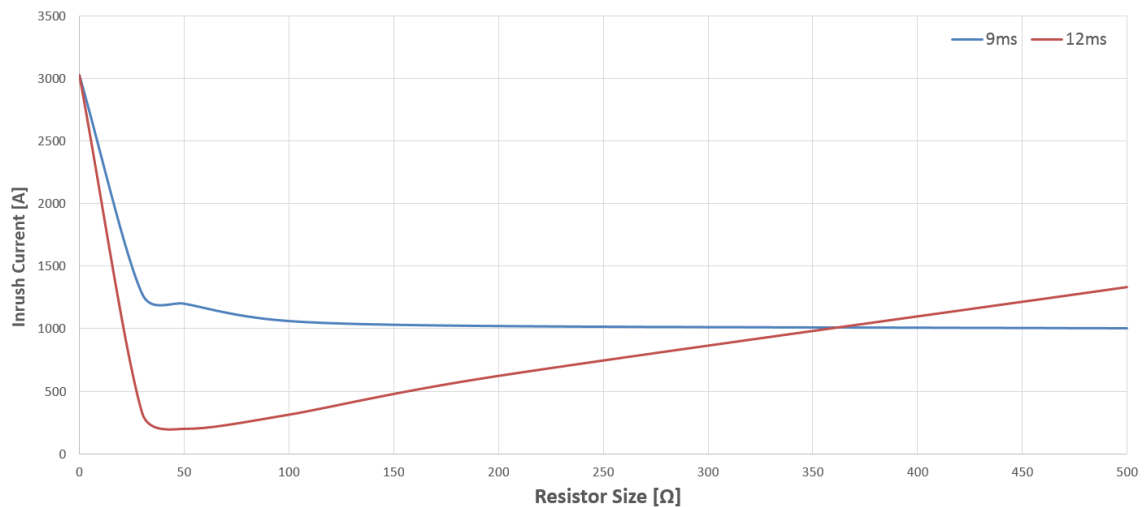


Figure 7
Optimal Resistance

To further investigate the effect of the insertion time, simulations were performed with the optimal 50 Ohm resistor insertion time varied over a range of 1 ms to 16 ms. Figure 8 shows the performance of the 50 Ohm resistor varies significantly with the insertion duration. The inrush current was reduced to 50% of its original maximum value when the insertion time was 8 ms. A 12 ms insertion time reduced the inrush currents to approximately 8% of the original maximum value. It was also noticed that insertion times longer than 12 ms did not further improve the performance.

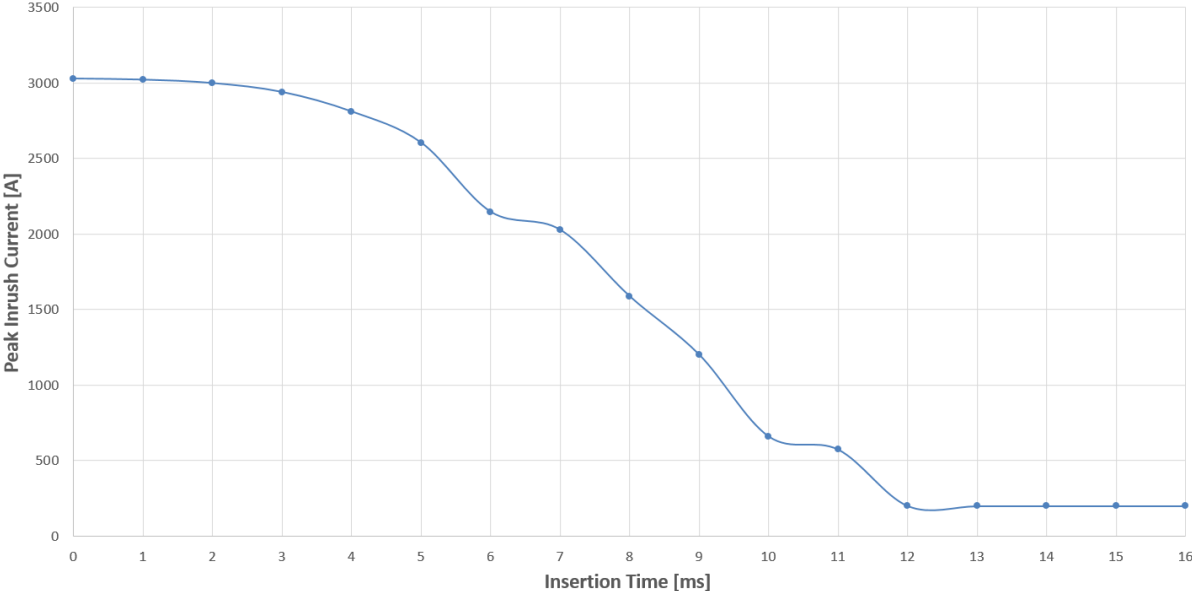


Figure 8
Effectiveness of Insertion Time

With the optimal resistor size, 50 Ohms, and insertion duration, 12 ms, we can further investigate their performance. Figures 9 and 10 show the resulting inrush currents and voltages measured on the primary side of the transformer, respectively and Figure 11 shows the rms voltage dip on phase A.

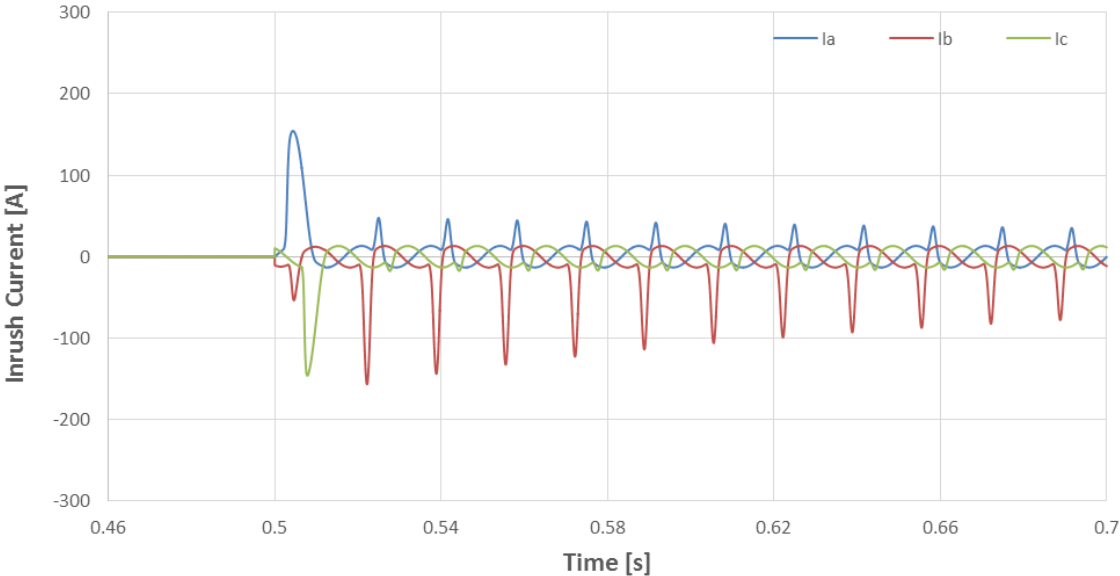


Figure 9
Transformer Inrush Current with Closing Resistor & Residual flux

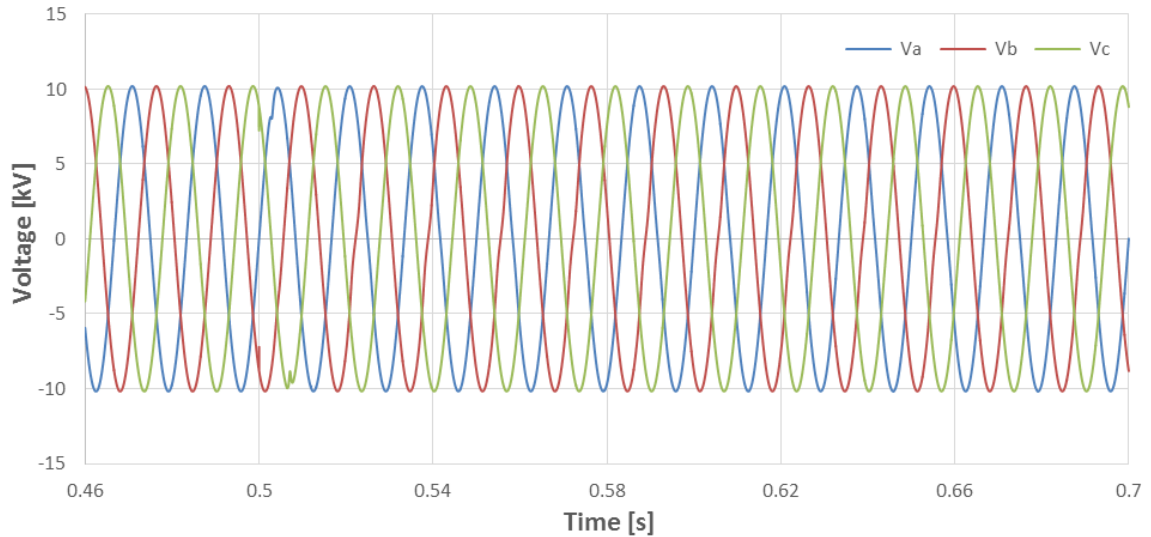


Figure 10
Transformer Primary Voltage with Closing Resistor & Residual flux

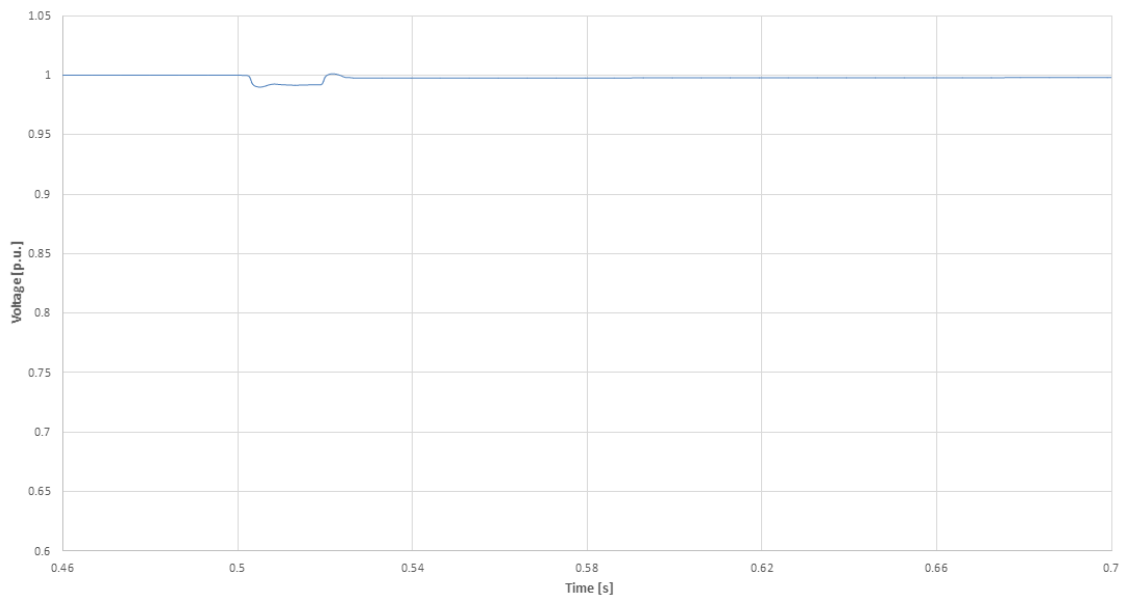


Figure 11
Transformer Primary Voltage, Phase A, with Closing Resistor & Residual flux

The inrush current in phase A increased to 150 A peak within the 1st cycle after energization and the voltage on the primary side dropped to 0.99 pu. Even with a large residual flux and a worst-case timing of the energization, the 50 Ohm closing resistor with a 12 ms insertion time reduced the step voltage drop to just 1%, well within the limits of the utility.

III. Summary and Conclusions

The troublesome issues of renewable interconnections on weak electric grids can be implemented with simple direct methods. The use of switching devices with closing resistors limit transformer inrush currents and the resulting step voltage drops to acceptable levels. IPO switching devices, sophisticated point-on-wave controllers, flux sensing, and de-fluxing are not needed.

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