Auctioneering Diodes: Pros and Cons

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***Abstract*—Auctioneering diodes are often proposed as a method for providing uninterruptible power to d.c. loads from two sources. Although the basic concept of auctioneering diodes is straight-forward, there are many nuances that should be understood before employing them. In particular, this paper discusses common-mode current issues with asymmetric auctioneering diode configurations as well as potential voltage doubling due to double ground faults in symmetric configurations. The design of snubbers and transient surge suppressors is also detailed.**

***Keywords*—auctioneering diodes, d.c. distribution, uninterruptible power, snubber, transient surge suppression**

I. Introduction

Asymmetric auctioneering diodes as depicted in Fig. 1 are often considered as a means to provide uninterruptible power to d.c. loads. The voltage at the load V_l (with respect to the common negative conductor) will be the higher of V_a and V_b less the diode voltage drop and voltage drop in the feeder cables. In this configuration, one of the sources is the normal supply to the load, while the other is the alternate supply. The voltage on the normal source is typically set to a slightly higher voltage than the alternate source and therefore supplies most if not all the required current to the load. With perfect conductors having zero impedance, the source with the higher voltage would supply all the power. In real systems with cable impedance, the lower voltage source may still supply power. Should the voltage on the normal source fall significantly below the voltage on the alternate for any reason, then the load will automatically shift to the alternate supply. The voltage on the normal source could fall below its set-point for a number of reasons including a fault within the source or a short-circuit between the normal source and its auctioneering diode. This automatic and uninterrupted transition of load power from one source to another is the primary reason auctioneering diodes are considered for high priority loads.

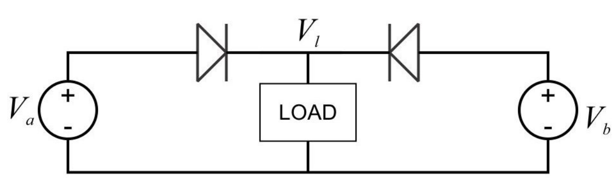


Fig. 1. Basic asymmetric auctioneering diode configuration

If the two sources implement a droop characteristic, then the load can be shared between them. The nonlinear characteristics of the diodes and sources present challenges in controlling load sharing both in the steady-state and dynamically. These characteristics may even result in load sharing when the intent is to power the load from a single source. In other cases interactions between the two sources can result in high frequency oscillations in the current provided by each source; even though the load current stays relatively constant. Reference [1] details several of the challenges associated with using auctioneering diodes.

II. Asymmetric Auctioneering Diodes

While the asymmetric auctioning diode configuration of Fig. 1 is effective at providing continuity of power in cases of a line-to-line short circuit on the source side of a diode, a line-to-line short-circuit on the load side will result in both sources experiencing a short-circuit. To minimize the amount of cable that is at risk of causing a line-to-line fault impacting both sources, the auctioneering diodes are generally co-located with the loads. To clear a line-to-line fault in the cable or load, a means to interrupt the short-circuit current must be provided. Typical solutions include circuit breakers, fuses, or the source detecting the over-current and shutting down.

Fig. 2 depicts the use of auctioneering diodes for multiple loads and the incorporation of circuit breakers to protect the cables between the sources and the auctioneering diodes. The circuit breakers and the associated connections on the source side are typically located within a load center or power panel.

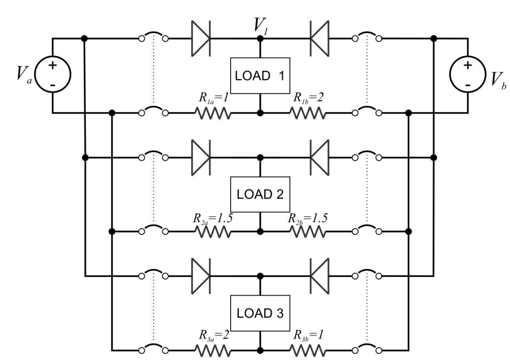


Fig. 2. Auctioneering diode configuration for multiple loads with circuit breakers

One issue with this configuration is that with the negative conductors tied together, the current returns back to the source via multiple paths. Assume the source on the right of Fig. 2 is providing 100 amps to Load 1 only. Also assume the negative conductors have the relative resistance values depicted on Fig. 2. This condition can be modeled as shown in Fig. 3.

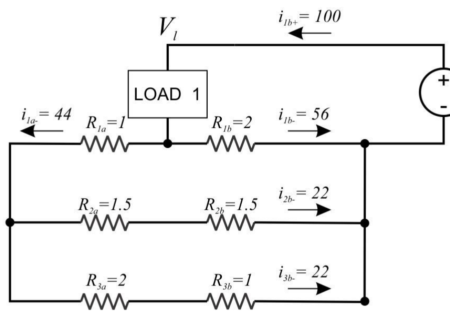


Fig. 3. Multiple return paths with auctioneering diodes

For this case, only 56% of the current returns directly back to the source on the right. The remaining 44% of the current returns via the common bus on the left side. Because the currents in each of the feeder cables for all of the loads are not equal and opposite, a common mode current exists. For the feeders for Load 1, the common mode flows from right to left with a value of 22 amps. For the feeder cables associated with Loads 2 and 3, the common mode current flows from left to right with the 22 amps split equally (11 amps) for the two feeder cables. The current loops for the common mode current are likely to be very large, meaning the magnetic fields they create are not cancelled and can be a source of significant electromagnetic interference (EMI) if common mode filters are not provided. Additionally, the large common mode currents may result in malfunctioning of the trip elements in the circuit breakers. Note that if Load 2 and Load 3 are drawing current, their contribution to the current through the Load 1 negative conductor will reduce to a degree the Load 1 common mode current.

This common mode behavior was observed during physical testing at the Florida State University (FSU) Center for Advanced Power Systems (CAPS) which resulted in circuit breakers unexpectedly tripping. A Simulink model was created as depicted in Fig. 4 and used to simulate a number of scenarios that varied the source voltages and cable impedances. Fig. 5 shows the results for one such scenario with unequal source voltages and unequal cable impedances. In all cases, there is a significant difference between the magnitude of the currents on the positive and negative conductors of the feeder cables.

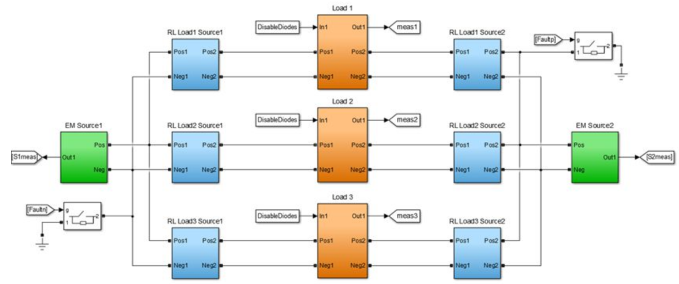


Fig. 4. Simulink Auctioneering Diode Model

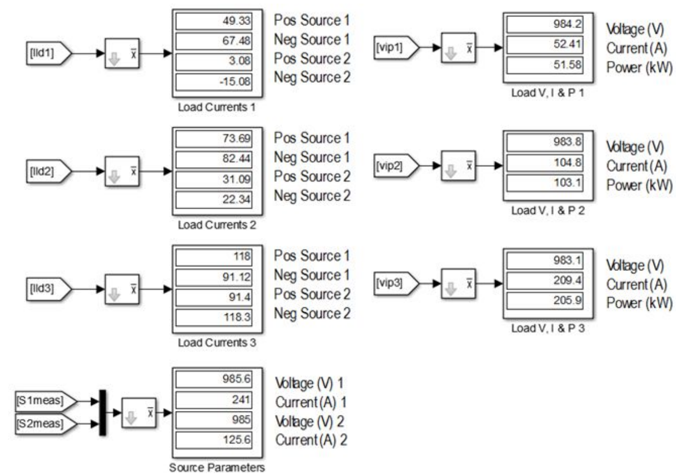


Fig. 5. Simulink Auctioneering Diode Model results for unequal sources and unequal cable impedances

III. Symmetric Auctioneering Diodes

One way to prevent the common mode currents associated with asymmetric configurations is to also insert auctioneering diodes in the negative conductors in a symmetric configuration as depicted in Fig. 6. The Simulink simulation of this configuration (Fig. 7) confirms the absence of common mode currents: positive and negative currents in each feeder cable are equal.

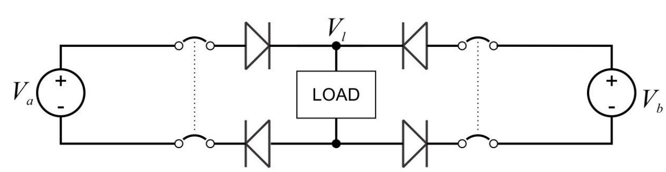


Fig. 6. Symmetric auctioneering diodes

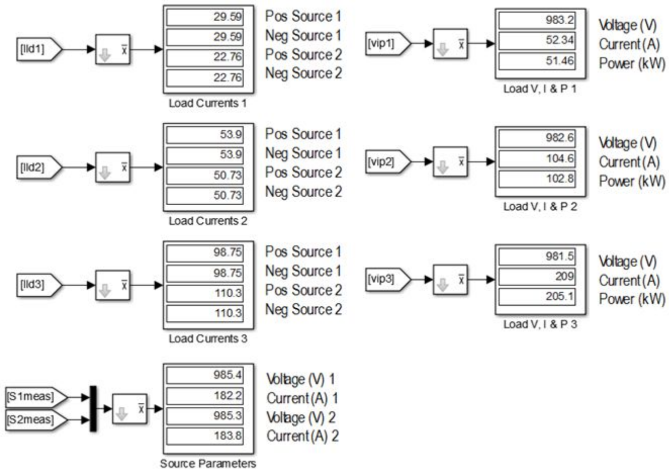
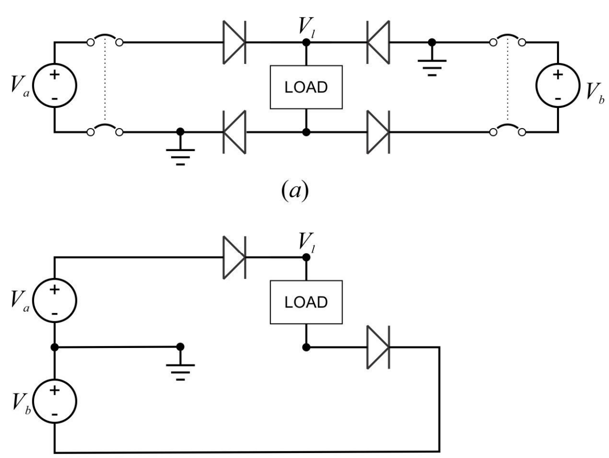


Fig. 7. Simulation results for symmetric auctioneering diodes

While the additional auctioneering diodes are effective in eliminating the common mode currents, they add a significant vulnerability in the case of a double ground fault as depicted in Fig. 8. The double ground fault places the two voltage sources in series with the upper left and bottom right diodes conducting. The load consequently is exposed to twice the nominal voltage and will likely not survive the event, unless designed to do so.

Fig. 9 presents the results of a Simulink simulation of the double ground fault with symmetric auctioneering diodes. A ground fault was applied to the negative rail of Source 1 at 1 second. As expected, this ground fault is not observed on the differential voltage for each of the loads. At 1.5 seconds, a second ground fault was applied to the positive rail of Source 2, resulting in a near doubling of the differential voltage for each load.



(*b*)

Fig. 8. Symmetric auctioneering diodes with double ground fault (*a*) and with non-conducting diodes and circuit beakers removed (*b*)

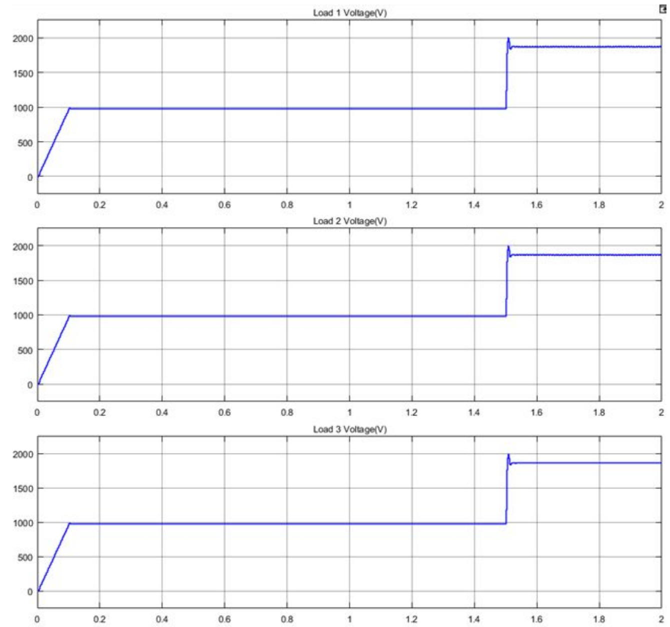


Fig. 9. Simulation results for symmetric auctioneering diodes with double ground fault

IV. Converter Topology

The topology of converters that make up the voltage sources may result in large circulating currents as well. Reference [2] describe some of the challenges when using three level converters. Detailed simulations should be conducted for normal operation, mode changes, and fault conditions to ensure a system of converters will behave appropriately when employing auctioneering diodes.

V. Snubbers

Auctioneering diodes may require snubbers to manage the reverse recovery events when the diode turns off. The need for snubbers arises specifically when the diode has to turn off currents with a high rate of fall of current (di/dt). As shown in Fig. 10, before a diode turns off, a reverse recovery current flows for a short time. During a fault on the source side, the current through the diode will fall with a di/dt governed by the load side voltage, the line inductance, and the fault resistance. If the alternate voltage source is not faulted and about the same voltage as the faulted source (prior to being faulted), the load side voltage remains approximately the pre-fault voltage. And, if the fault resistance is low (bolted fault) and a snubber is not used, the di/dt is to the first order only a function of the inductance between the diode and the fault. In many cases, that inductance is low resulting in a high di/dt. Therefore, it is important to carefully analyze the circuit and determine if the diode can manage the resulting di/dt without a snubber or if a snubber is required. Snubbers for diodes usually consist of a series combination of a resistance (R_s) and Capacitance (C_s) as shown in Figure 11.

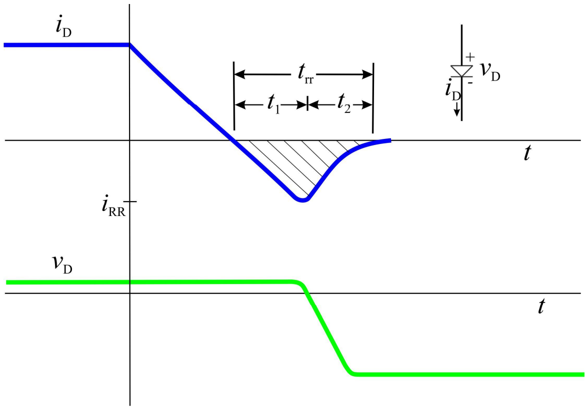


Fig. 10. Diode reverse recovery characteristic.

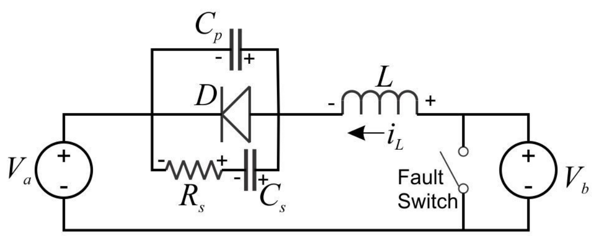


Fig. 11. Diode Snubber

One potential issue with using a snubber is that when the diode is not conducting, the snubber provides a relatively low impedance path for high frequency current to flow between the two sources. The interaction of the snubbers with the source and load filters and power electronic controls should be investigated through detailed modeling and simulation to ensure power quality and component operation remain within design parameters.

The analysis of this snubber circuit is straight-forward. Ignoring C_p (the diode body capacitance) for the time being, after closing of the fault switch, the diode will conduct while the inductor current ramps down. In an ideal diode, once the current dropped to zero, the diode would turn off. In physical diodes however, the diode (and inductor) current will pass through zero until it reaches the diode's peak reverse recovery current at which time the current rapidly decays to 0. If we consider $t = 0$ to occur when the peak reverse recovery current is achieved, the initial conditions are given by (1) and the associated differential equations by (2) and (3).

$$i_L(0) = -i_{RR} \qquad V_{CS}(0) = 0 \tag{1}$$

$$-V_a = L\frac{di_L}{dt} + R_s i_L + V_{CS} \tag{2}$$

$$i_L = C_s\frac{dV_{CS}}{dt} \quad \text{or} \quad \frac{di_L}{dt} = C_s\frac{d^2V_{CS}}{dt^2} \tag{3}$$

Combining (2) and (3) results in (4)

$$-V_a = LC_s\frac{d^2V_{CS}}{dt^2} + R_sC_s\frac{dV_{CS}}{dt} + V_{CS} \tag{4}$$

If we assume a solution to (4) to be of the form (5), using traditional differential equation techniques, the solutions for a_1 and a_2 are given by (6).

$$V_{CS} = A_1e^{a_1t} + A_2e^{a_2t} + A_3 \tag{5}$$

$$-\frac{R_s}{2L} \pm \sqrt{\frac{R_s^{\ 2}}{4L^2} - \frac{1}{LC_s}} \tag{6}$$

For a snubber design, common practice is to prevent oscillation of the response (i.e. "ringing") by having the response slightly underdamped, critically damped or overdamped. The circuit is critically damped when the square root term of (6) is zero. The circuit will be underdamped (and ring if the resistance is too small) if the roots are complex. The circuit will be overdamped if the roots are real.

To limit the initial voltage spike, the voltage drop across the diode should typically be limited to the line voltage V_a or alternately some value safely below the maximum reverse breakdown voltage (V_{rm}). Remember that when the diode stops conducting, the current is $-i_{RR}$, and the capacitor voltage is 0, thus the maximum value for R_S can be calculated:

$$R_s = \frac{V_a}{i_{RR}} \tag{7}$$

While V_a is known with some certainty, i_{RR} is not. Thus a reasonable upper bound for i_{RR} should be used. Datasheets for diodes for example, may not list the peak reverse recovery current so its value must be inferred from other parameters provided.

The reverse recovery time (t_{rr}) of a diode is the time required to charge the capacitance associated with the pn-junction to a value which corresponds with the reverse voltage. The following parameters determine the peak reverse current i_{RR} and recovered charge Q_{rr} :

(1) The characteristics of the pn-junction,

(2) Initial current,

(3) Temperature, and

(4) Current rate of change during turn off.

There are two extreme cases which define boundaries for determining the severity of the recovery as depicted in Fig. 10:

Case 1: Fast recovery $t_2 \cong 0$ and $t_1 = t_{rr}$ (snappy)

$$t_{rr} = \sqrt{\frac{2Q_{rr}}{di_D/dt}} \qquad i_{RR} = \sqrt{2Q_{rr}\left(\frac{di_D}{dt}\right)} \tag{8}$$

Case 2: Very 'Soft' Recovery $t_2 = t_1 = t_{rr}/2$

$$t_{rr} = \sqrt{\frac{4Q_{rr}}{di_D/dt}} \qquad i_{RR} = \sqrt{Q_{rr}\left(\frac{di_D}{dt}\right)} \tag{9}$$

It may be necessary to test devices experimentally to determine the parameter values.

Typically, overvoltage is produced when the energy contained in the circuit inductance charges the diode body capacitance to a value which exceeds the breakdown voltage. This is more likely the case with "snappy" diodes where $t_2 \approx 0$ since the circuit inductance has no path other than body capacitance immediately following the point where the maximum reverse current i_{RR} is reached. In many cases, a snubber is the solution to the overvoltage by adding both a way to capture and dissipate unwanted charge.

The minimum value for the capacitance can be calculated by examining the critically dampened case (10).

$$C_s = \frac{4L}{R_s^2} \tag{10}$$

L is also not usually known with certainty, so to avoid the snubber from being significantly underdamped, an upper bound should be chosen for *L*. While the circuit will be underdamped if C_s is somewhat less than indicated in (10), the response will be faster. Eliminating the factor of 4 in (10) achieves a faster response which decays fast enough to preclude ringing in what can be called an "optimal" response [3]. Going back to Fig. 11, the value for C_s should also be chosen so it is at least 3 times as large as C_p to minimize the impact of C_p on the dynamics [3] but which may result in an over-damped response. In any case, simulations should be conducted with more detailed models of the system to ensure adequate performance over the range of parameter uncertainty.

For completeness, the remaining coefficients to solve (5) are provided in (11).

$$\begin{aligned} A_4 &= -\frac{i_{RR}/(C_s a_1) + V_a}{a_2/a_1 - 1} \\ A_2 &= V_a - A_2 \\ A_3 &= -V_a \end{aligned} \tag{11}$$

This procedure was employed after the occurrence of an auctioneering diode failure at CAPS during fault testing in late 2018. The Simulink model in Fig. 12 was created to understand and correct the issue. The diode module was an IXYS MDO 500-20N1 with a maximum reverse breakdown voltage of $V_{rm} = 2.0\text{kV}$ and a maximum average forward current of $I_{FWDavg} = 560\text{A}$. The manufacture provided a reverse recovery charge of $Q_{rr} = 1.5\text{mC}$. The data sheet specified a junction capacitance of $C_J = 576\text{pF}$. However, the junction capacitance is usually not useful for snubber calculations due to a dominant body or package capacitance. Therefore, the body capacitance was measured resulting in $C_p = 21\text{nF}$. Finally, the worst-case reverse recovery was assumed where the diode snaps off when it reaches i_{RR} yielding reverse recovery times of $t_{rr} = t_1 = 7\mu\text{s}$ and $t_2 = 0\mu\text{s}$. Other circuit parameters included in the model were the measured current rate of change $di_D/dt = 20\text{A}/\mu\text{s}$, the circuit inductance $L = 50\mu\text{H}$ and the buss voltage $V_{buss} = 1.0\text{kV}$.

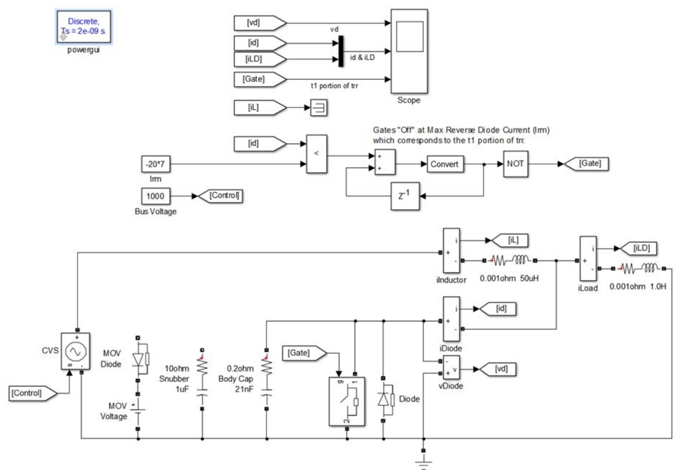


Fig. 12. Diode snubber Simulink model

Without a snubber in the system, the reverse voltage across the diode approaches 8kV as shown in Fig. 13. This is nearly four times the manufacturer's maximum reverse voltage (2kV) and will more than likely destroy the device. A snubber should be applied to the device to prevent over-voltage. Generally, the optimal solution is a slightly under-damped. However, if this is insufficient to suppress over-voltage, the system may be over-damped by adjusting the snubber resistance and/or by passive clamping using a metal-oxide varistor (MOV).

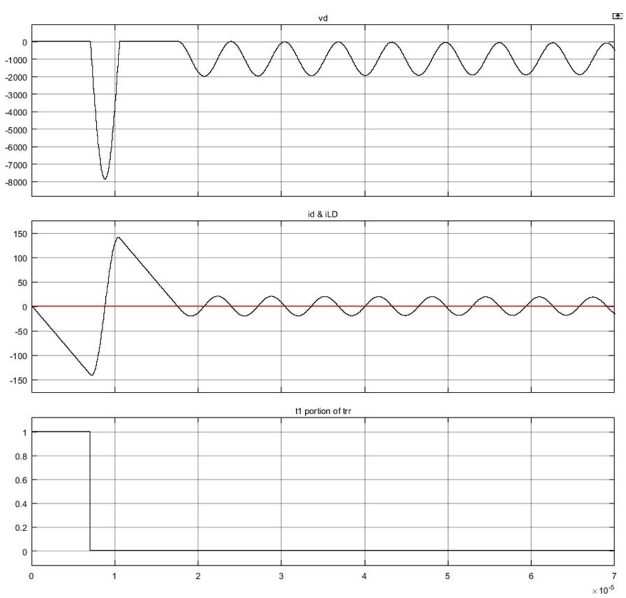


Fig. 13. Simulation results for no snubber

For the optimally damped (slightly underdamped) case (Fig. 14), a metalized polypropylene film capacitor ($C_s = 1\mu F$) was used based on manufacturer's recommendation along with a snubber resistance R_s of 49Ω. Based on (7), this resistance is too high which is reflected in the peak reverse voltage exceeding the maximum reverse diode voltage of 2kV. However, it should be noted that the peak reverse voltage is indeed lower than with no snubber, and the Fig 14. voltage and current waveforms display a slightly under-damped system unlike the oscillatory nature shown in Fig. 13 [3].

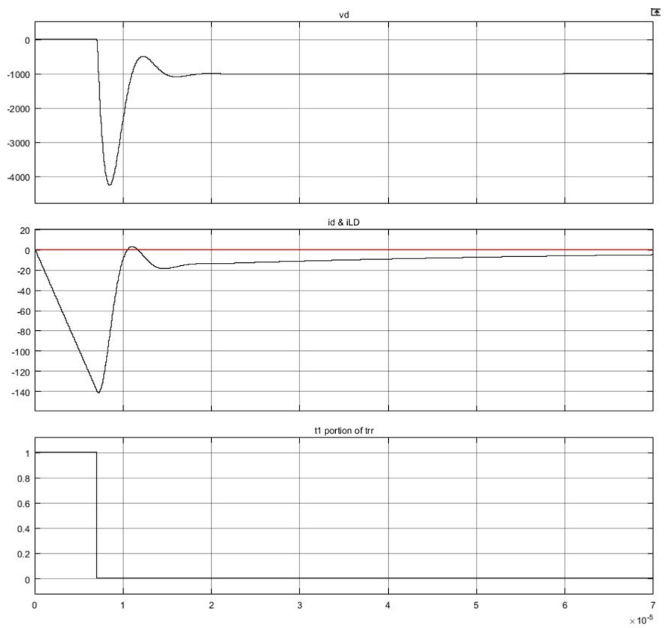


Fig. 14. Simulation results for optimally damped snubber

The manufacturer recommended a snubber resistance of 10Ω making the system over-damped. The snubber resistance in this case is more than sufficient in preventing the reverse voltage from exceeding the maximum diode limit of 2kV. As displayed in Fig. 15, the reverse voltage is contained to roughly 1.5kV. The simulation is in agreement with the manufacturer's recommended snubber components of $C_s = 1\mu F$ and $R_s = 10\Omega$. These RC values are more than sufficient to contain the over-voltage. Further, an MOV is also recommended in parallel with the device as extra protection. Since the diode is generally in the on-state, the likelihood of an MOV failure is low especially if it is rated closer to the 2kV diode limit.

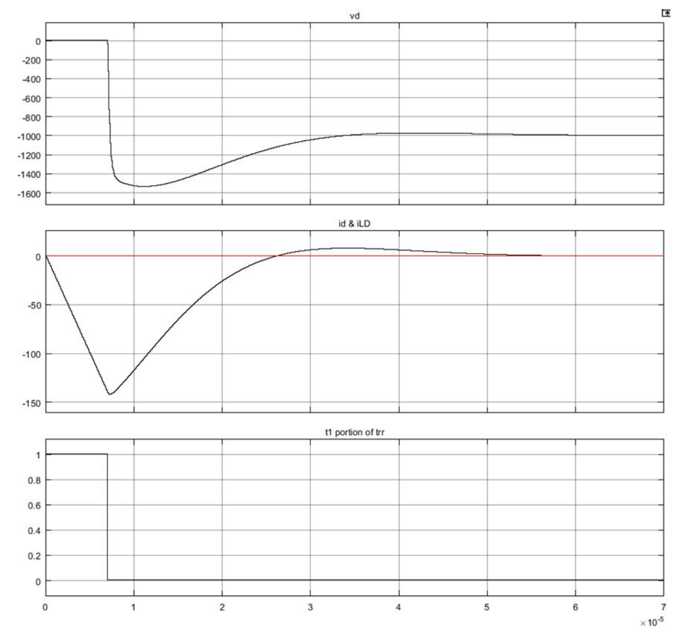


Fig. 15. Simulation results for over damped snubber

VI. Transient Surge Suppression [4]

The use of a transient protection device such as an MOV as shown in Fig. 16 is often a viable choice for non-repetitive voltage suppression. The MOV can be provided in addition to the snubber circuit, or alone if transfer of power from the normal to alternate source occurs infrequently.

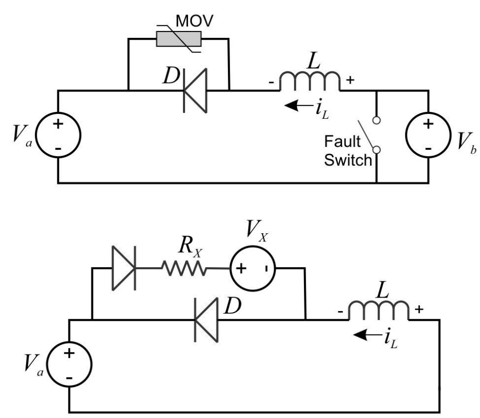


Fig. 16. Transient protection device inserted into a circuit and the equivalent model.

Given a suitable relationship between the source or circuit reactance and internal resistance of the MOV, a sufficient amount of energy will be absorbed by the device preventing a destructive voltage across the equipment or device terminals. The nonlinear VI characteristic of a typical MOV is shown in Fig. 17.

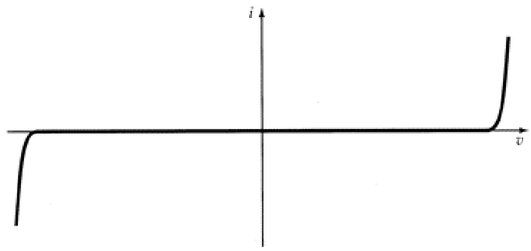


Fig. 17. Nonlinear VI characteristic of a typical MOV [4].

The modeling equations for a typical MOV are listed below based on the equivalent circuit model shown in Fig. 16.

$$\begin{aligned} i_X &= \frac{V_a - V_X}{R_X}\left(1 - e^{-\frac{t}{\tau}}\right) \text{ where } \tau = \frac{L}{R_X} \\ v_D &= V_X + R_X i_X \\ v_D &= V_X + (V_a - V_X)\left(1 - e^{-\frac{t}{\tau}}\right) \end{aligned} \tag{12}$$

As an example, let us assume the voltage disturbance profile matches the reverse voltage spike found in the plot shown in Fig. 13. This plot contains an 8kV spike (V_a) lasting 0.333µs. However, the diode voltage should be limited to a peak value of $v_D \leq 2.0\text{kV}$. Further, the protective device element is modeled by a voltage source (V_X) in series with a resistance (R_X) as shown in Fig. 16. Let us assume $V_X = 1.5\text{kV}$ and R_X is unknown. This means the maximum MOV resistance R_X is defined by (13) based on the circuit inductance $L = 50\mu\text{H}$ from Section V.

$$\begin{gathered} v_D = V_X + (V_a - V_X)\left(1 - e^{-t/\tau}\right) \\ 2000 = 1500 + (8000 - 1500)\left(1 - e^{-0.333\mu/\tau}\right) \\ \tau = 4.1603\mu\text{s} \\ R_X = L/\tau = \boxed{12\Omega} \end{gathered} \tag{13}$$

Since the peak inductor current in Figures 13, 14 and 15 is 140A, the energy in the fault may be calculated per (14).

$$W = \frac{1}{2} L I_D^2 = 0.49\text{J} \tag{14}$$

MOVs are generally rated by voltage and energy absorption capability, so rough estimates of the source of the voltage and energy must be understood. For a power line application, this is generally a fairly easy determination. However, attempting to suppress non-repetitive voltage spikes too close to the breakover voltage of the MOV may result in MOV destruction via leakage current. Further, the device is intended for non-repetitive energy absorption. Thus as expected, utilizing MOVs in switching circuits that may result in repetitively exercising the device has been problematic. Ideally, the voltage across the MOV should be low and stable most of the time. For the case of an auctioneering diode application, these are precisely the conditions.

The decision as to whether a snubber circuit or MOV should be employed in any given design depends on the expected operating conditions, availability of devices with required ratings and tolerances, reliability, weight, size, and cost. Designers are encouraged to conduct a trade-study including detailed modeling and simulation to determine the best design.

VII. Conclusions

While auctioneering diodes may appear to be a simple means of providing uninterruptible power to a d.c. load within a d.c. distribution system, this apparent simplicity masks the actual complexity. To limit common mode currents, auctioneering diodes should be provided on both the positive and negative supplies. To account for a potential double line to ground fault, loads should be designed to survive over voltages of at least twice the normal supply voltage for as long as it takes to clear line the ground faults. Voltage spikes resulting from line inductance interacting with the turn-off of the reverse recovery current of the auctioneering diodes may need to be suppressed to a level that the diodes can tolerate. The interaction of the components used to suppress the voltage spikes with the load and source filters should be investigated through modeling and simulation to ensure power quality and component operation remain within design values.

Acknowledgment

The authors thank FSU CAPS for relaying their lessons learned from extensive testing of auctioneering diode configurations.

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